AD-751 854

A SECONDARY POWER SYSTEM STUDY FOR ADVANCED ROTARY-WING AIRCRAFT

Bernard H. Nicholls

Garrett Corporation

Prepared for:

Army Air Mobility Research and Development Laboratory

August 1972

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USAAMRDL TECHNICAL REPORT 72-13

A SECONDARY POWER SYSTEM STUDY FOR ADVANCED ROTARY-WING AIRCRAFT

By

Bernard H. Nicholls

August 1972

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

CONTRACT DAAJ02-70-C-0048
AiRESEARCH MANUFACTURING COMPANY
A DIVISION OF THE GARRETT CORPORATION
PHOENIX , ARIZONA

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*

AiResearch Manufacturing Company
A Division of The Garrett Corporation
402 South 36th Street, Phoenix, Arizona

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

A SECONDARY POWER SYSTEM STUDY FOR ADVANCED ROTARY-WING AIRCRAFT

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Technical Report

5. AUTHOR(S) *(First name, middle initial, last name)*

Bernard H. Nicholls

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 1972	343	

8a. CONTRACT OR GRANT NO.

DAAJ02-70-C-0048

b. PROJECT NO.

c. Task 1G162203D14415

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

USAAMRDL Technical Report 72-13

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

SY-6103-R

STATEMENT A

10. DISTRIBUTION STATEMENT

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Eustis Directorate
U. S. Army Air Mobility R&D Laboratory
Fort Eustis, Virginia

13. ABSTRACT

A study was performed to define and evaluate secondary power systems for an advanced Army rotary-wing aircraft, using existing technology and two advanced technology levels.

The basic aircraft mission, performance penalty parameters, and system components are defined. From a total of 152 candidate systems, 36 were selected for detailed comparisons. Evaluation parameters included incremental takeoff gross weight, system weight, volume, reliability, maintainability, availability, vulnerability, complexity, and life-cycle cost. The recommended system comprises an integral-bleed/shaft-power APU that drives into the aircraft accessory gearbox with two electrical generators and two hydraulic pumps. Main engines are started pneumatically by bleed air from the APU. Cockpit cooling was an optional addition, and an air-cycle system was selected.

With current technology advancements, this system is predicted to reduce takeoff gross weight by 11 percent for 1975 production aircraft and by 26 percent by 1985.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

1a

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Helicopter Secondary Power System						

Unclassified
Security Classification

8442-72

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DEPARTMENT OF THE ARMY
U. S. ARMY AIR MOBILITY RESEARCH & DEVELOPMENT LABORATORY
EUSTIS DIRECTORATE
FORT EUSTIS, VIRGINIA 23604

The study described herein was conducted by the AiResearch Manufacturing Company of Arizona under the terms of Contract DAAJ02-70-C-0048. The work was performed under the technical management of Mr. Paul Chesser, Propulsion Division, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory.

The object of this study effort was to determine three optimum secondary power systems (SPS) for advanced rotary-wing aircraft, using three levels of technology, and to recommend the research and development required to achieve technological advancements in SPS components which could provide significant improvements for future aircraft.

Appropriate technical personnel of this Directorate have reviewed this report and concur with the findings contained herein.

Costing and required program levels described are the views of the contractor and are not necessarily the views of the Eustis Directorate, USAAMRDL. Therefore, caution is recommended in the use of those data.

This report is recommended for use in planning secondary power systems for future Army rotary-wing aircraft.

Task 1G162203D14415
Contract DAAJ02-70-C-0048
USAAMRDL Technical Report 72-13
August 1972

A SECONDARY POWER SYSTEM STUDY FOR ADVANCED ROTARY-WING AIRCRAFT

Final Report

AiResearch Report Sy-6103-R

By

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Prepared by

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Phoenix, Arizona

for

EUSTIS DIRECTORATE
U.S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

ABSTRACT

The objectives of this study were to: (1) define and evaluate secondary power systems (SPS) for an advanced Army rotary-wing aircraft using the design requirements of the Utility Tactical Transport Aircraft System (UTTAS) design study; and (2) recommend the required R&D. These objectives were to be attained for SPS, utilizing today's technology and two advanced technology levels, with and without the inclusion of an environmental control system (ECS)--refrigeration package for cockpit cooling.

The basic aircraft mission and performance penalty parameters were defined from the results of a survey of helicopter manufacturers. SPS component manufacturers were surveyed, and studies were completed to determine the evaluation parameters of performance, weight, and volume of all SPS components and subsystems, and to ascertain installation requirements. The survey and studies also emphasized other evaluation parameters, such as reliability, maintainability, and life-cycle cost.

Twenty-seven basic candidate SPS were identified. These were analyzed for three technology levels, with and without the addition of an ECS, for a total of 162 systems. A preliminary elimination analysis was based on the system evaluation parameters of incremental takeoff gross weight (ΔTOGW) and system weight and volume, which reduced the total candidate systems to 36. The final analysis of the remaining systems included these three parameters plus reliability, maintainability, availability, system vulnerability, system and aircraft complexity, and life-cycle cost. The takeoff gross weight comparison accounted for the fuel used for the assumed mission profile as well as installed weight. The final SPS evaluation was based on the weighted effect of each of the 10 parameters enumerated above.

The recommended SPS selected from the systems analysis comprises a single-shaft integral-bleed APU mounted on the accessory gearbox with two electrical generators and two hydraulic pumps. A hydraulic accumulator starting system is used for APU starting. An air turbine starter, powered by APU bleed air, starts the main engine. The ECS was an optional addition to the SPS, and an air-cycle system was recommended.

Technology advancements from the prescribed R&D tasks are predicted to reduce SPS takeoff gross weight penalty of the recommended system without ECS--11 percent for the 1975 production period and 26 percent for the 1985 production period. For the recommended system with ECS, 22- and 38-percent reductions are predicted.

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FOREWORD

This report was prepared by the AiResearch Manufacturing Company of Arizona. The work was accomplished under Contract DAAJ02-70-C-0048, Task 1G162203D14415, with the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia. Mr. B. H. Nicholls directed the program for AiResearch.

The author wishes to acknowledge the contributions made to this program by many individuals within The Garrett Corporation: A. D. Meshew, editor; L. W. Norman and G. J. Amarel, advanced APU design; K. K. Sorenson, pneumatic starters and drives; R. R. Steves, environmental control systems; J. B. Picone, Coordinator for electrical systems; R. N. Sullivan, Coordinator for hydraulic systems; and D. S. Alexander and W. G. Harrach, Systems Analysis programming.

The author also wishes to acknowledge the contributions made to this program by the following companies: Vertol Division, Boeing Company; Bell Helicopter Company; Lockheed California Company; Sikorsky Aircraft; Abex Corporation; Aero Hydraulics, Inc.; New York Air Brake Company; Vickers, Inc.; General Electric, Lear-Siegler, Inc., Rotax Aircraft Equipment, Ltd.; Westinghouse; and Janitrol Aero Division.

The study was conducted over the period from June 1, 1970, to May 31, 1971.

TABLE OF CONTENTS

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TABLE OF CONTENTS - Continued

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS - Continued

LIST OF ILLUSTRATIONS - Continued

LIST OF ILLUSTRATIONS - Continued

LIST OF ILLUSTRATIONS - Continued

LIST OF ILLUSTRATIONS - Continued

LIST OF ILLUSTRATIONS - Continued

LIST OF ILLUSTRATIONS - Continued

LIST OF TABLES

LIST OF TABLES - Continued

LIST OF TABLES - Continued

LIST OF TABLES - Continued

1. INTRODUCTION

This document summarizes a study that defines and evaluates secondary power systems (SPS) for an advanced Army rotary-wing aircraft, selects an optimum system for each of three specified technology levels, and recommends required R&D where technology advances are required.

The aircraft system design requirements, as defined for the Utility Tactical Transport Aircraft System (UTTAS), were used as the basis for the study, to define secondary power systems for each of three technology levels:

I. An aircraft system that enters production in 1975 and incorporates an SPS, utilizing existing technology

II. An aircraft system that enters production in 1975 and incorporates an SPS, utilizing advanced technology compatible with the production time period

III. An aircraft system that enters production in 1985 and incorporates an SPS, utilizing advanced technology compatible with the production time period

For the study, the UTTAS airframe design requirements were held constant for each of the three SPS technology levels. This simplifying assumption does not affect the validity of the study results.

2. PROGRAM OUTLINE AND APPROACH

The program was conducted according to the plan presented below and shown graphically in Figure 1. The following subsections summarize the various tasks as referenced in Figure 1.

2.1 TASK I - SURVEYS

2.1.1 Task Ia - Survey of Airframe Companies

All airframe companies that were previously awarded UTTAS study contracts were contacted to define the UTTAS performance capabilities and mission characteristics to determine a consensus of SPS requirements and aircraft penalty factors for the three technology levels.

2.1.2 Task Ib - Survey of Component Manufacturers

Concurrent with Task Ia, leading SPS component manufacturers were contacted to obtain information on components of specific size or range of sizes (or power) covering the potential candidate system requirements (see Subsection 2.3.1). A complete hardware description and the design and development status of the components for each of the three technology levels were requested.

2.1.3 Task Ic - Airframe and Component Manufacturers Survey Results

At the conclusion of the survey phase, the data were correlated and summarized. From this information, representative parameters were established for subsequent tasks.

2.2 TASK II - CANDIDATE SYSTEM SELECTION AND PARAMETRIC APU CYCLE STUDY

2.2.1 Task IIa - Candidate System Selection

To form a basis for a parametric APU cycle study (Task IIb), a preliminary selection of basic candidate systems was made as a result of the Task Ia survey. This task was also required to more clearly define requirements for the component manufacturers.

For this study, basic systems included the APU, APU starting system, main engine starting system, accessory gearbox and driven accessories, and the power distribution system to

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interconnect these components. Basic systems also included provisions for ventilation cooling of the cockpit, cabin and avionics, and heating for the cockpit and cabin.

2.2.2 Task IIb - Parametric APU Cycle Study

To form a basis for selection of APU cycles to be considered in subsequent tasks, a parametric APU cycle study was conducted. Information from Tasks I and IIa was used to determine the type of output power and duty cycle required of the APU, its operating environment, and its required service life. From these considerations, the initial component efficiencies, pressure drops, cooling flow, accessory horsepower, and parasitic losses were estimated as a function of cycle, pressure ratio, turbine inlet temperature, bleed air fraction, and recuperator or regenerator effectiveness.

The cycle pressure ratios considered were from 2:1 to 20:1, turbine inlet temperatures from 1600° to 2400°F, and bleed-air pressure ratios from 2:1 to 6:1. The basic cycles analyzed included: single-shaft and multispool integral bleed types, and single-shaft and free-turbine types for use with a load compressor. Each of these was analyzed parametrically. The effects of variable geometry and regeneration were included. In addition, a combined APU/environmental control system (ECS) was considered.

Candidate cycles derived from the parametric analysis were evaluated for initial manufacturing cost, maintainability, reliability, complexity, vulnerability, and life-cycle considerations.

2.3 TASK III - SECONDARY POWER SYSTEMS STUDY

2.3.1 Task IIIa - Secondary Power Systems Function Trade-Off Studies

For this program, the SPS is defined as a subsystem of the complete aircraft, consisting of all secondary power producing and transmission components that comprise the APU, APU starting system, main engine starting system, the accessory gearbox and driven accessories (hydraulic pumps, electrical generators, air compressors, etc.), the power distribution system and controls interconnecting these components, and the environmental control system.

The components or subsystems associated with specific functional requirements were evaluated to determine the appropriate design, performance, and installation parameters necessary to permit the evaluation and comparison of candidate systems

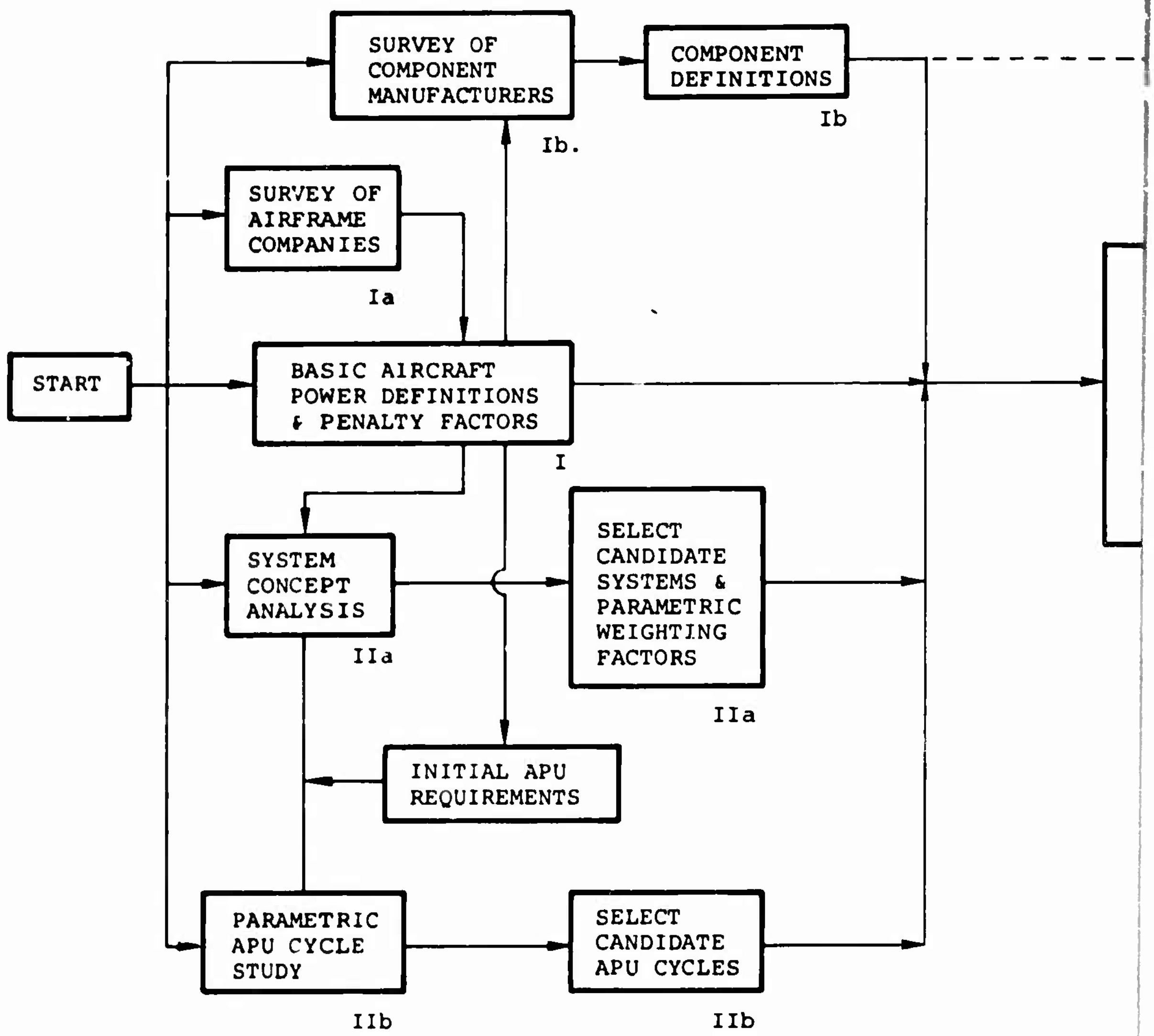
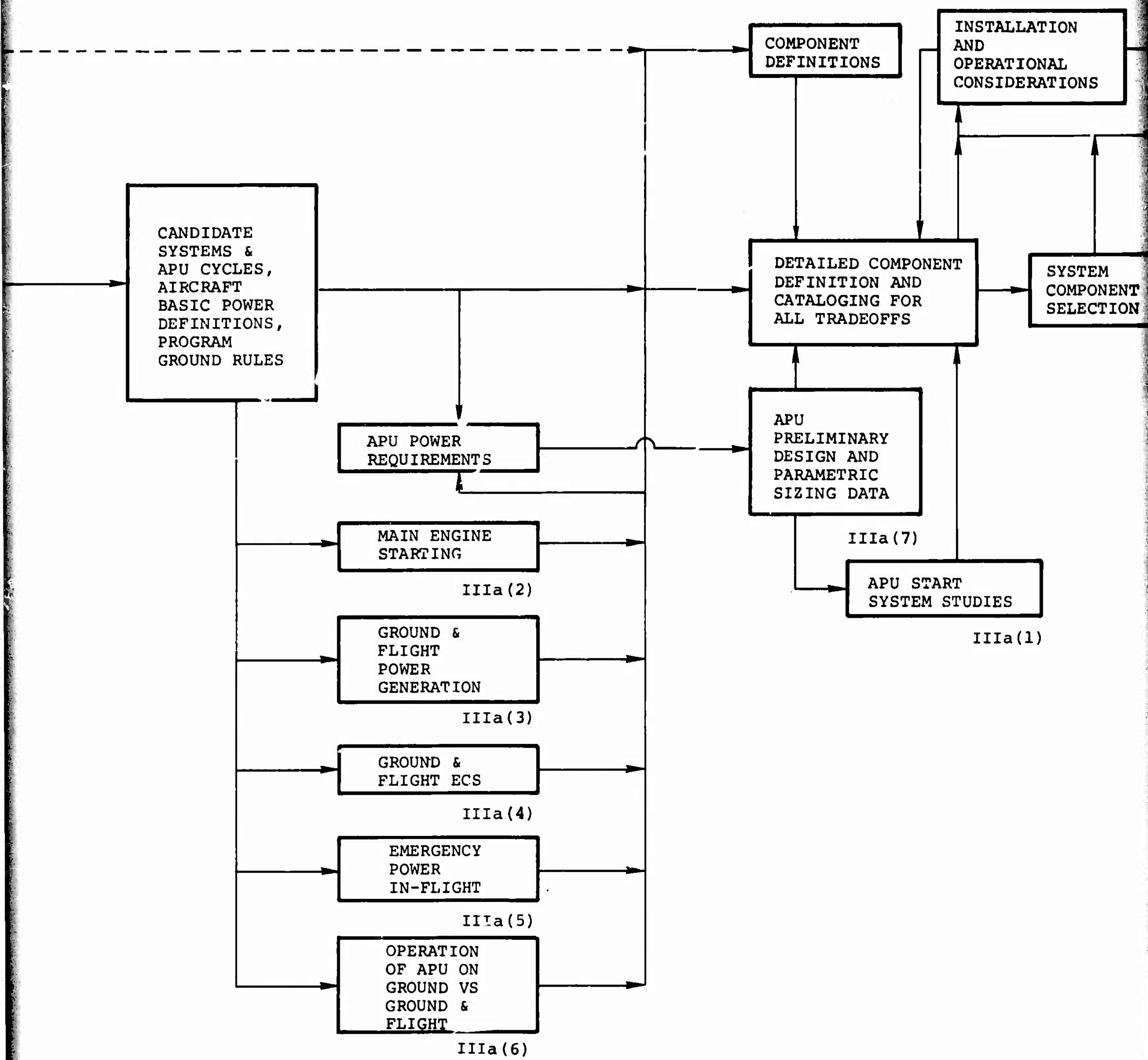
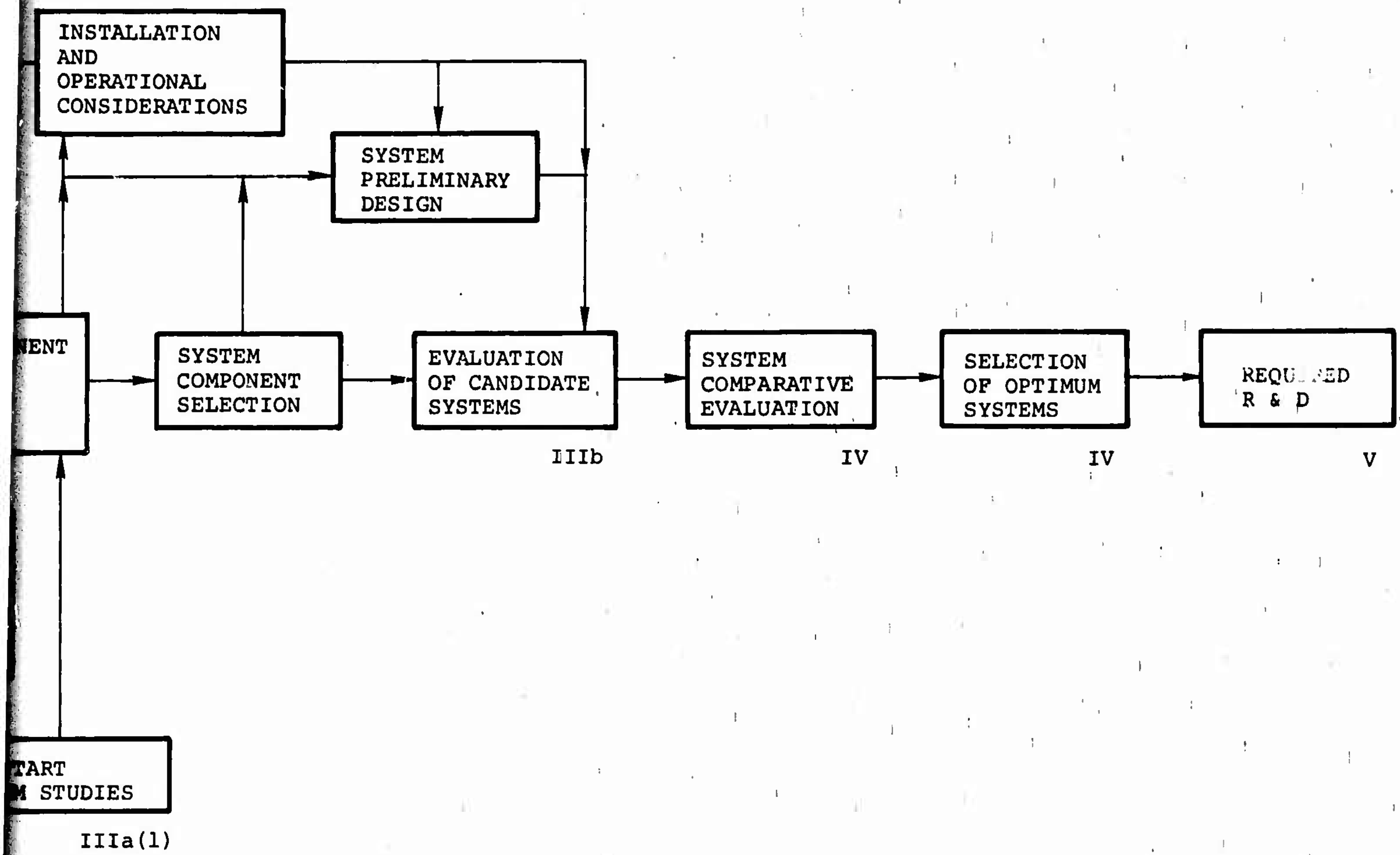


Figure 1. Secondary Power System Study for Advanced Aircraft Overall Program Logic.


COMPONENT DEFINITIONS
INSTALLATION AND OPERATIONAL CONSIDERATIONS
CANDIDATE SYSTEMS & APU CYCLES, AIRCRAFT BASIC POWER DEFINITIONS, PROGRAM GROUND RULES
DETAILED COMPONENT DEFINITION AND CATALOGING FOR ALL TRADEOFFS
SYSTEM COMPONENT SELECTION
APU POWER REQUIREMENTS
APU PRELIMINARY DESIGN AND PARAMETRIC SIZING DATA
IIIa(7)
MAIN ENGINE STARTING
IIIa(2)
APU START SYSTEM STUDIES
IIIa(1)
GROUND & FLIGHT POWER GENERATION
IIIa(3)
GROUND & FLIGHT ECS
IIIa(4)
EMERGENCY POWER IN-FLIGHT
IIIa(5)
OPERATION OF APU ON GROUND VS GROUND & FLIGHT
IIIa(6)



INSTALLATION AND OPERATIONAL CONSIDERATIONS
SYSTEM PRELIMINARY DESIGN
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SYSTEM COMPONENT SELECTION
EVALUATION OF CANDIDATE SYSTEMS
SYSTEM COMPARATIVE EVALUATION
SELECTION OF OPTIMUM SYSTEMS
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M STUDIES
IIIa(1)

selected under subsequent tasks. The evaluations conducted under this task consisted of establishing the following component or subsystem parameters consistent with the technology levels:

1. Weight
2. Volume
3. Reliability
4. Vulnerability
5. Maintainability
6. Complexity
7. Life-cycle cost

Trade-off studies were performed for the following SPS subsystem or component functions.

<u>Task IIIa(1) - APU Starting</u>

An analysis of appropriate systems was conducted using the design criteria established by the Task I survey to select candidate APU starting systems. The analysis consisted of specific component-sizing studies to determine the primary evaluation parameters defined above. Integration of the APU starting system with the SPS and other aircraft systems was considered.

<u>Task IIIa(2) - Main Engine Starting</u>

A main engine starting system analysis was conducted using representative engine starting characteristics and starting system design criteria, as defined from the results of Task I. Power input and component size requirements for each system were established. Starter output torque curves and engine starting times were determined for each basic type of starting system. Integration of the main engine starting system with other aircraft systems was considered.

An emergency main engine starting system independent of the APU was investigated. Although this system is intended for ground use in remote areas, in-flight operation was also considered.

Task IIIa(3) - Ground and Flight Power Generation

From the basic aircraft power requirements established in Task I and the candidate systems selected in Task IIa, trade-offs were conducted to determine the type of equipment to produce the required electrical, hydraulic, and pneumatic power.

Task IIIa(3a) - Electrical System

Trade-offs were conducted to determine the necessary electrical or motor generator types and controlling and power-conditioning components for each candidate system. The potential location of the generator and the speed-governing characteristics of the driving equipment (main engine, transmission gearbox, or APU) were considered.

Task IIIa(3b) - Hydraulic Pumps

Applicable hydraulic system components were evaluated according to the requirements determined from the Task I survey and the established candidate systems.

Task IIIa(3c) - Air Compressors

The production of pneumatic power was evaluated on the basis of a separate aerodynamic-type air compressor that may be driven by the APU and/or the main engine. [The effect on APU design for integral bleed or integrated, driven compressor/APU designs is included in Task IIIa(7).] Both in-flight and/or ground operation were considered, where the compressor may supply all or part of the aircraft pneumatic power. Pneumatic system requirements include such functions as main engine starting and ECS.

Task IIIa(4) - Ground and Flight ECS

An evaluation to determine the effect of including an environmental control system was made. The effect on the SPS evaluation parameters was established for comparison to basic systems with ventilation for cooling in lieu of an ECS. Systems were evaluated primarily on the basis of heating and cooling loads for the cockpit and avionics.

Task IIIa(5) - Emergency In-Flight Power Generation

The available power from each candidate APU was checked to determine the possibility of emergency use in flight.

The effects of component sizing and performance on the APU production of emergency power and on other aircraft systems or

components were considered, provided integration of the primary SPS components could be achieved.

The parameters determined from this task were used in the candidate system evaluations to show the effects of including emergency power generation in flight.

Task IIIa(6) - Operation of APU on the Ground and In Flight Versus Ground Operation Only

The effect on APU performance and the required component evaluation parameters was determined for in-flight operation of APU designed for ground operation only. Supplementing or supplanting main engine power extraction for SPS functions was considered. These functions include the electrical, hydraulic, and pneumatic power requirements of the aircraft in flight and the capability of furnishing shaft power directly to the rotor, thereby making full use of APU power in critical aircraft operating modes. The influence of installation requirements and operational environments on the design criteria of APU for in-flight and ground operation was also investigated.

Items in the APU installation and operation were:

1. Mounting
2. Environmental effects
3. Inlet and exhaust systems
4. Fire zone considerations
5. Cooling provisions
6. Containment armor
7. Controls, instrumentation, and readouts

Task IIIa(7) - Final APU Sizing and Preliminary Design

An analysis was conducted to establish APU designs that best met the operating requirements of the individual candidate systems. The designs were for basic APU cycles, as derived from the parametric study, and/or other cycles applicable to system variations resulting from the functional trade-off studies. A combined APU/ECS (air cycle) was also studied.

Parametric APU sizing data were generated to permit adaptation of the basic APU to changes in power levels in the various candidate systems. These data included size, weight, and fuel consumption as functions of APU power rating. Altitude operational effects were also included.

2.3.2 Task IIIb - Evaluation of Candidate Systems

All candidate systems were evaluated on the basis of the following parameters for each of the technology levels:

1. System weight
2. System volume
3. Takeoff gross weight influence
4. System availability
5. System reliability
6. System vulnerability
7. System maintainability
8. Effect on aircraft system complexity
9. Secondary power system complexity
10. Secondary power system life-cycle cost

Evaluation systems were of components selected from the trade-off and optimization analyses of previous tasks and include the necessary interconnecting ducts, mounts, installation allowances, and power transmission items chargeable to each system. The matrix of systems being evaluated consisted of each trade-off item, with variations in types of components for a specific function, and the system changes associated with the component changes in the gearbox, ducting, mounting, etc.

Systems were judged on the basis of performance and evaluation factors, modified by weighting factors, to assign the importance of each in the overall consideration. The performance evaluation consisted of a comprehensive takeoff-gross-weight analysis for both fixed and expendable weight penalties and accounted for aircraft weight alteration (structural, fuel, tankage, engine, installation penalties), as a result of variations in SPS component weight and performance. The evaluation parameters were for vulnerability, aircraft complexity,

and SPS complexity. Other parameters are calculated items, including weight, volume, reliability, maintainability, and availability.

2.3.3 Task IIIc - SPS Preliminary Design

To support the evaluation of systems, limited preliminary designs were made of components defined by previous tasks. Components such as hydraulic pumps, generators, and the APU were integrated with the necessary gearboxes or other power transmissions to interconnect with functional systems and to indicate aircraft interfaces.

2.4 TASK IV - COMPARATIVE EVALUATION

A comparative evaluation of the systems selected under Task III and the optimum from this task for the rating comparison data generated in Task III(b) above. Optimum systems were selected for each technology level and time period with and without an ECS and a redundant main engine starting system.

An outline drawing was prepared for the selected SPS.

2.5 TASK V - REQUIRED R&D

Technological advancements required for design of the 1975 and 1985 production systems and the required R&D to achieve these technological levels are defined in detail. The tasks for these advancements are delineated, including the objectives, approach, risk, and justification for each. Estimates of total cost and man-hours to complete the individual technology advancement tasks are included. Areas where performance improvement may be achieved by more than one technological advancement are justified. The scope of application and the relative priority are also assessed.

3. SURVEYS

Airframe companies and component manufacturers were surveyed to establish a basis for the study. This section summarizes the results of the surveys and interviews.

3.1 AIRFRAME COMPANIES

Mission parameters and secondary power system requirements were determined from a survey of the airframe companies awarded UTTAS study contracts. From the results, certain aircraft design and performance parameters, penalty factors, secondary power system performance requirements, and types of SPS equipment were defined.

Information was obtained from four airframe companies and, therefore, represented four different aircraft designs. When the information was in close agreement, the data were used as an average. When diverse data were obtained, a representative selection was made that was most consistent with other compiled data and the mission requirement. Occasionally, only a single input was available.

The evaluation method of this study does not depend upon exact parameters but only that certain basic information be established for all SPS studies. The emphasis in this phase of the program was to obtain the most representative information available. The results of compiling and selecting data from this survey was a composite basic secondary power system, the basic operating requirements, and the necessary parameters to conduct the SPS studies, as discussed in the following paragraphs.

3.1.1 Basic System

The arrangements of the secondary power system contained basic similarities that are apparently typical of the aircraft. The basic system, from which the trade-off studies and alternate SPS arrangements were made, is shown in Figure 2 and consists of the following:

1. The main engines drive into the main rotor transmission through freewheel devices. This will permit either or both engines to drive the rotor and will also facilitate autorotation of the main rotor in the event of main engine loss.

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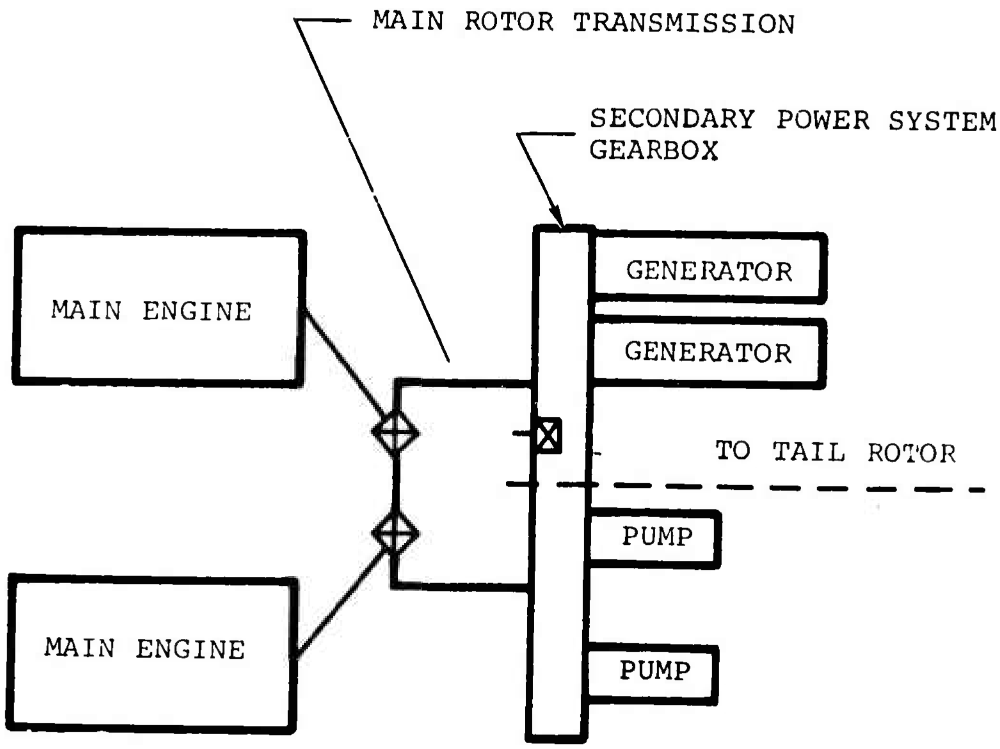

Figure 2. Basic System Schematic.

2. The basic SPS components (electrical generators and hydraulic pumps) and the tail rotor are driven from the main rotor transmission. This permits a direct power path to the accessories at all times, i.e., from the rotor during autorotation.

3. The basic SPS components are two electrical generators (sized for redundant electrical requirements) and two hydraulic pumps. One pump supplies power to the primary flight control system, the other (a utility pump) to a redundant flight control system.

The main engines are free-turbine types that transmit power from the power turbine directly to the drive system at essentially constant speed. The electrical generators and hydraulic pumps are normally driven within a narrow speed range of approximately 5 percent, varying to 10 percent for a small portion of the time. Speed-compensating devices for the accessories are not required. The accessory gearbox may be attached to, or may be an integral part of, the main rotor transmission.

The main engine starting system, the APU starting systems, and the method of power distribution between these subsystems are not shown in Figure 2, since the definition of these items is subject to trade-off studies and varies for each system.

3.1.2 Power Requirements

The composite system power requirements used throughout the remainder of the program are shown on Table I, which includes only the basic power from the system and miscellaneous cooling loads and no power transmission losses. These loads are functions of the individual system trade-offs. The specific columns of Table I are defined as follows:

1. Operating Mode - The APU is considered as the power source during engine start, checkout, and maintenance operations. The main engines are assumed to be operating during the standby mode just prior to takeoff. Only the cruise conditions are listed for the flight mode, since most of the mission profile is at this condition and the study results are not affected by this simplification.

2. Ambient Conditions - This column is the range of ambient conditions at sea level and other specifics at which the listed power levels must be furnished.

TABLE I. COMPOSITE AUXILIARY POWER REQUIREMENTS

Operating Mode	Ambient Conditions	Power Requirements				Remarks
		Duration	Electrical** (kva)	Hydraulic (gpm)	Cooling*	
Engine Starting	-65° to 130°F at S.L. and 95°F at 4000 ft	30 sec at 59°F	3***	-	-	Advance technology 1500 hp engine
Checkout and Maintenance	-65° to 130°F at S.L., and 95°F at 4000 ft	15 min 15 min	13 -	- 8	2700 w dissipation	
Standby	-65° to 130°F at S.L., and 95°F at 4000 ft	5 min	15	1	2700 w dissipation	
Cruise	-65° to 130°F at S.L., 95°F at 4000 ft, and -12°F at 20,000 ft	3 hr	9 avg 40 peak	5 avg 8 peak	2700 w dissipation	

*An optional additional requirement is 15,000 Btu/hr cockpit cooling.
**Electrical power is primarily 400 Hz ac but may include up to 200 amp dc.
***Additional to engine starting power.

3. <u>Duration</u> - All durations are approximate but are considered typical for the advanced vehicles under consideration.

4. <u>Electrical Power</u> - The 3 kva required during engine starting is arbitrary but representative of the expected additional load during the starting cycle. The 13 kva for checkout and maintenance is an average of the electrical loads indicated by the survey. The standby-power estimate of 15 kva is considered representative of the maximum load at this condition. The 9-kva requirement at the cruise condition is an average of survey data for normal electrical power. The 40 kva represents a maximum load and includes full rotor de-icing.

5. <u>Hydraulic</u> - The hydraulic loads listed represent the limited data avilable for a 3000-psi system. A 3000-psi system was specified for a majority of the systems and is, therefore, considered representative of the aircraft. However, detailed loads were not readily obtainable from all sources.

6. <u>Cooling</u> - The assumed avionics heat dissipation is 2700 w. An optional air cycle environmental control system supplies cooling air for the cockpit, and the avionics would be cooled by fans drawing air from the cockpit. The ECS would also be used for ground cooling when supplied with bleed from the APU. The basic systems employ ventilating fans for cooling the cockpit and avionics, with the ECS as an optional system.

The SPS components required to furnish power to the basic system are shown on Table II. An 11-amp-hr battery was specified in the majority of cases. APU starting studies showed that this size battery was generally sufficient for APU starting, except at low ambient conditions. However, since this battery was also used in systems not employing electrical APU starting and dc power may be required for aircraft system functions when APU power is not needed on the ground, a standard size 11-amp-hr battery was included in the secondary power system.

One 40-kva electrical generator is required to furnish the system power. An identical generator is required for redundancy.

TABLE II. BASIC SYSTEM COMPONENTS				
Unit	No.	Rating	Type	Location
Battery	1	11 amp-hr	Ni-Cad	Airframe
Electric Generator	2	40 kva	400 Hz 115/200 v	Accessory gearbox
Hydraulic Pump	1	5 gpm	3000 psi var	Accessory gearbox
	1	8 gpm	3000 psi var	
ECS	1*	15,000 Btu/hr	Air cycle	Airframe

*Optional

Hydraulic power for the primary flight control system is furnished by a 5-gpm pump, while that for the utility and redundant flight control systems are supplied by an 8-gpm pump. The pumps are variable-delivery, 3000-psi types.

3.1.3 Aircraft and Engine Parameters

Composite aircraft and engine performance parameters, as determined from the survey, are shown on Table III. Since the vehicle gross weight is not used in the SPS analysis, a representative value of 15,000 lb was selected. In all cases, two engines rated at 1500 hp each were required.

The penalty factors for fixed and expendable weights--ΔTOGW/Δ installed weight and ΔTOGW/Δ fuel weight, respectively--are average values consistent with the 15,000-lb aircraft gross weight and engine power levels. The bleed-air extraction penalties are also considered representative for this class of engine and are linear to a bleed-air extraction of 5 percent of the engine throughflow.

3.2 COMPONENT MANUFACTURERS

Electrical and hydraulic component sizes, weights, performance, operating speeds, MTBF, TBO, cost, and recommended areas for R&D for the three technology levels were established from the results of the survey of component manufacturers. The equipment power levels of Table II were used as the basis for the survey inquiries.

TABLE III. AIRCRAFT AND ENGINE PARAMETERS	
Takeoff gross weight	15,000 lb
Number of engines	2
Power rating, each engine, 59°F, sea level	1500 hp
ΔTOGW/Δ installed weight	2.6
ΔTOGW/Δ fuel weight	2.1
ΔEngine hp/shp extracted	1:1
ΔEngine output hp/ΔW_B extracted at 60°F	2.8 pct/1 pct
at 95°F	3.3 pct/1 pct
ΔFuel, lb/hr/Δ bleed air, lb/min	1.4

3.2.1 Hydraulic Pumps

The basic aircraft system requires two hydraulic pumps, as described in Section 3.1.1 and Table II. Both are variable displacement types to efficiently accommodate the hydraulic loads. The 3000-psi system pressure was the choice of the component manufacturers contacted because of higher reliability and efficiency with little or no weight penalty, compared to a 4000-psi system.

The general trend indicates that advances in this range of pump sizes will be in the form of increased operating speed. The speed ranges, as functions of the displacement for the three technology levels, are shown in Figure 3. Lines of constant horsepower for 5 and 8 gpm are superimposed to illustrate the displacement decrease for the more advanced components. Since the weight and volume are functions of displacement, these parameters are readily obtained from Figure 3.

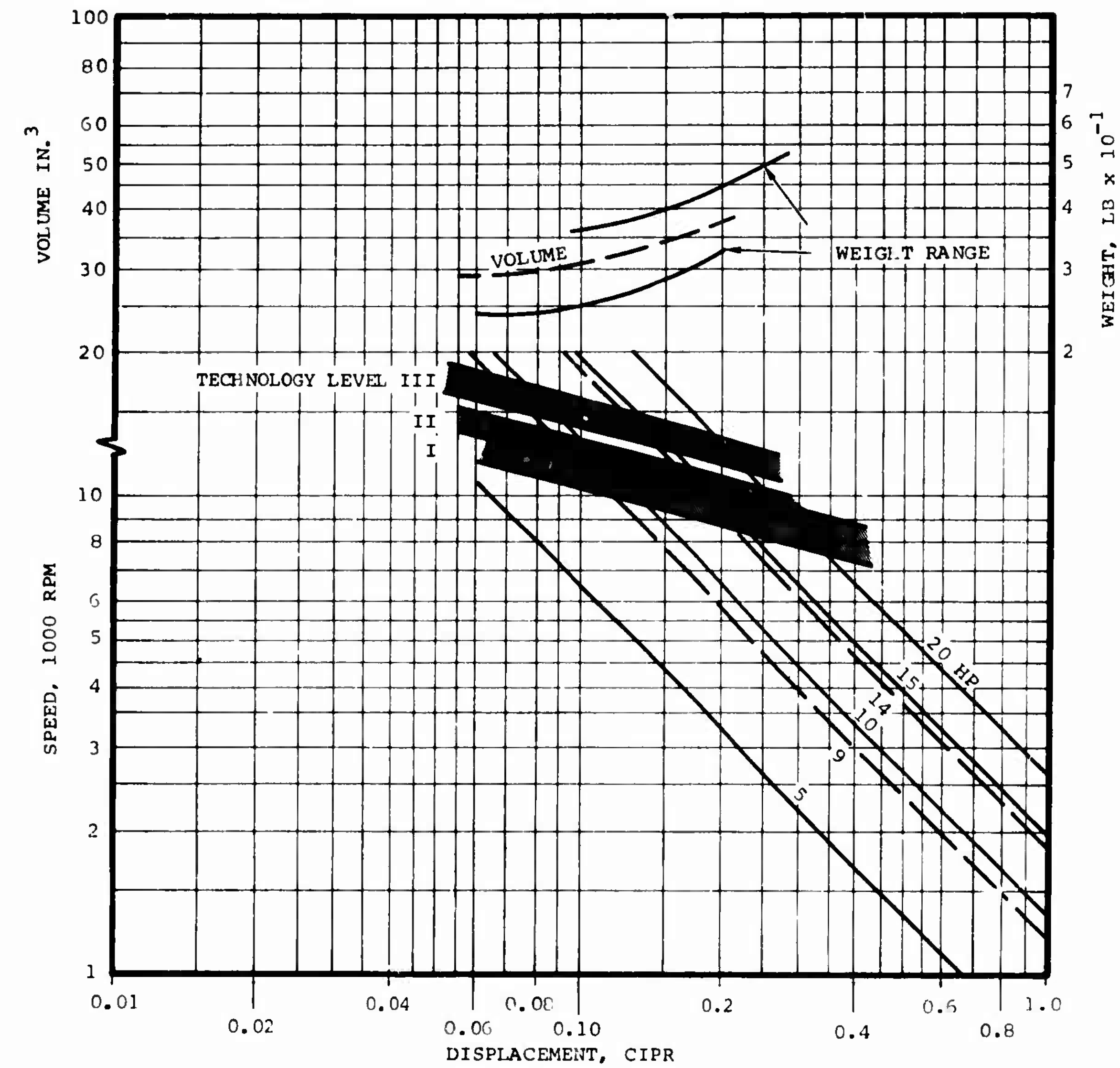

Figure 3. Hydraulic Pump Operating Speeds, Weights, and Volume.

Weight is shown in the upper portion of the curve as a function of pump displacement. The upper part of the weight curve is generally applicable to present technology designs. The lower part represents the more advanced designs. However, the spread between the two weight curves is rather small, with a total of approximately 1 lb.

The pump volume curve represents rather limited data but may be used to show trends, which generally follow the weight curve.

The information presented in Figure 3 represents "standard" pumps and does not include depressurizers and unloading valves that are special designs. The designs are all multiple piston, positive, variable displacement types in current use.

Data for efficiency, TBO, MTBF, and cost are shown in Table IV. The ranges indicate the spread of data received, but generally, all parameters increased with the advance in technology levels. It was difficult to compare TBO and MTBF, since these are directly related to the design, speed, and other operating conditions selected by the manufacturer. However, the data are indicative of trends. Cost information represents production prices for quantities of approximately 300 units. Future cost data were limited apparently because of the uncertainty in predictions.

The present state-of-the-art for military aircraft hydraulic systems is defined by MIL-H-5440, Type II (-65° to 275°F). Existing fluids and materials are ample to meet these requirements. The pump capacity of the helicopter system defined for this study is relatively low, and oil temperatures higher than 300°F are not realistic. Therefore, technology advances, specifically for higher operating temperatures, are not required, provided the system pressure level does not increase above the established level of 3000 psi.

Both Figure 3 and Table IV indicate that the principal advancement will be increased operating speed, with an attendant increase in reliability and life. This trend reflects improvements and refinements in present piston-valve plate designs. A new concept is required to show gains in excess of those indicated. One concept, which has been suggested, is a rotating port plate unit, wherein the cylinder block and

TABLE IV. HYDRAULIC PUMP SURVEY DATA			
	Technology Level		
Conditions	I	II	III
Efficiency (overall)	85	85-86	85-88
TBO, hr	760-1200	1000-2000	1250-2500
MTBF	6500-10,000	10,000-15,000	10,000-20,000
Unit cost:			
5 gpm	$400-850	$750*	$800*
8 gpm	$450-850	$875*	$900*

*Data available from one source.

pistons do not rotate. Windage losses would be reduced and higher speeds achieved. Other advanced system concepts (such as integrating the pump, reservoir, filters, and valves into a common housing or package) offer potential reductions in system weight, space, and transmission line lengths and should be considered for future systems. The fly-by-wire system is another advanced concept, with integrated hydraulic/electric power packages located in the specific vicinity of the aircraft where power is required.

3.2.2 Electric Generators

The aircraft electrical system requires a generating system that produces 40 kva, 400 Hz, 120/208 v of three-phase continuous power. Output power should meet the requirements of MIL-STD-704A--overload conditions of 150 and 200 percent rated power for 2 and 5 sec, respectively. Input speed regulation will be 5 and 10 percent for 90 and 10 percent of the time, respectively. Two identical generators are required per system for redundancy.

Generators of this size and meeting these requirements are currently available. A typical wound-rotor generator rated at 40-kva continuous duty would operate at a nominal speed of 12,000 rpm with an efficiency of 83 to 85 percent and would weigh 33 to 34 lb. Reduced weight and size are achieved in this design by the incorporation of oil spray cooling within the generator with the lubrication and cooling oil integrated with other areas of the secondary power system. A generator control unit (GCU) weighing approximately 3 lb is required as a part of the system and typically provides control of, and protection for, the system. The control functions include:

1. Voltage regulation
2. Anticycling
3. Line contactor control

The protection functions include protection against:

1. Overvoltage
2. Undervoltage
3. Overfrequency
4. Underfrequency
5. Feeder fault

The predicted trend in generator and control unit weights and volumes for this type of system is shown on Figures 4 and 5 for the 1970 to 1985 period. For 12,000-rpm generators, Figure 4 indicates a decrease in generator weight of about 10 percent, which is predicated on the application of materials researched for electromagnetic and mechanical properties. The corresponding decrease in volume predicted for this type of generator is 10 to 15 percent. The cumulative result of technical advancements and an increase in generator speed are also shown on Figure 4 to illustrate possible generator weight reductions. However, when generator speeds approach 20,000 to 25,000 rpm, the conventional 400 Hz is no longer applicable, since practical generator design dictates a higher frequency output. Utilization of this power requires rectifying the output for a dc system or acquiring wild frequency for resistive loads, with a small portion of the power converted to a close-tolerance, 400-Hz output.

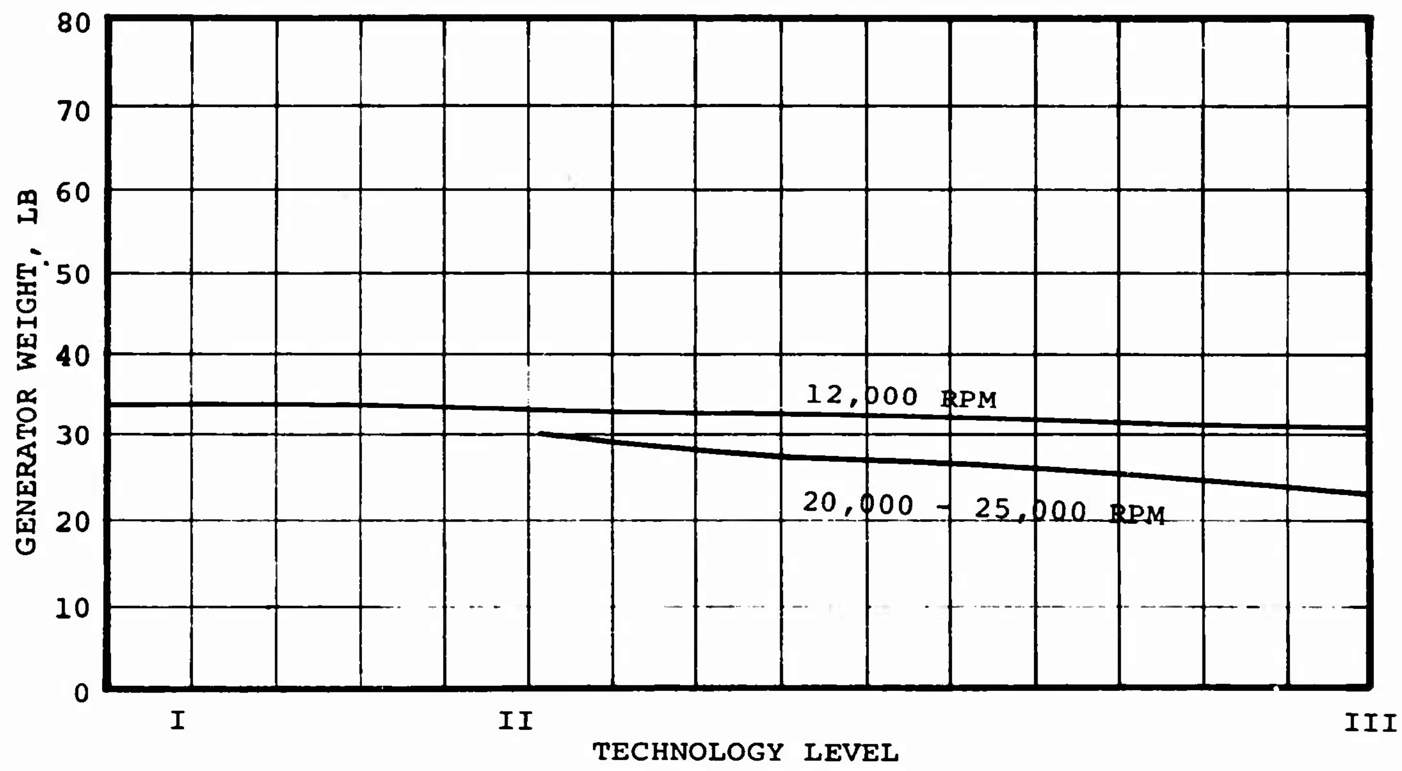

Figure 4. Generator Weight Trend, 40-kva Rating.

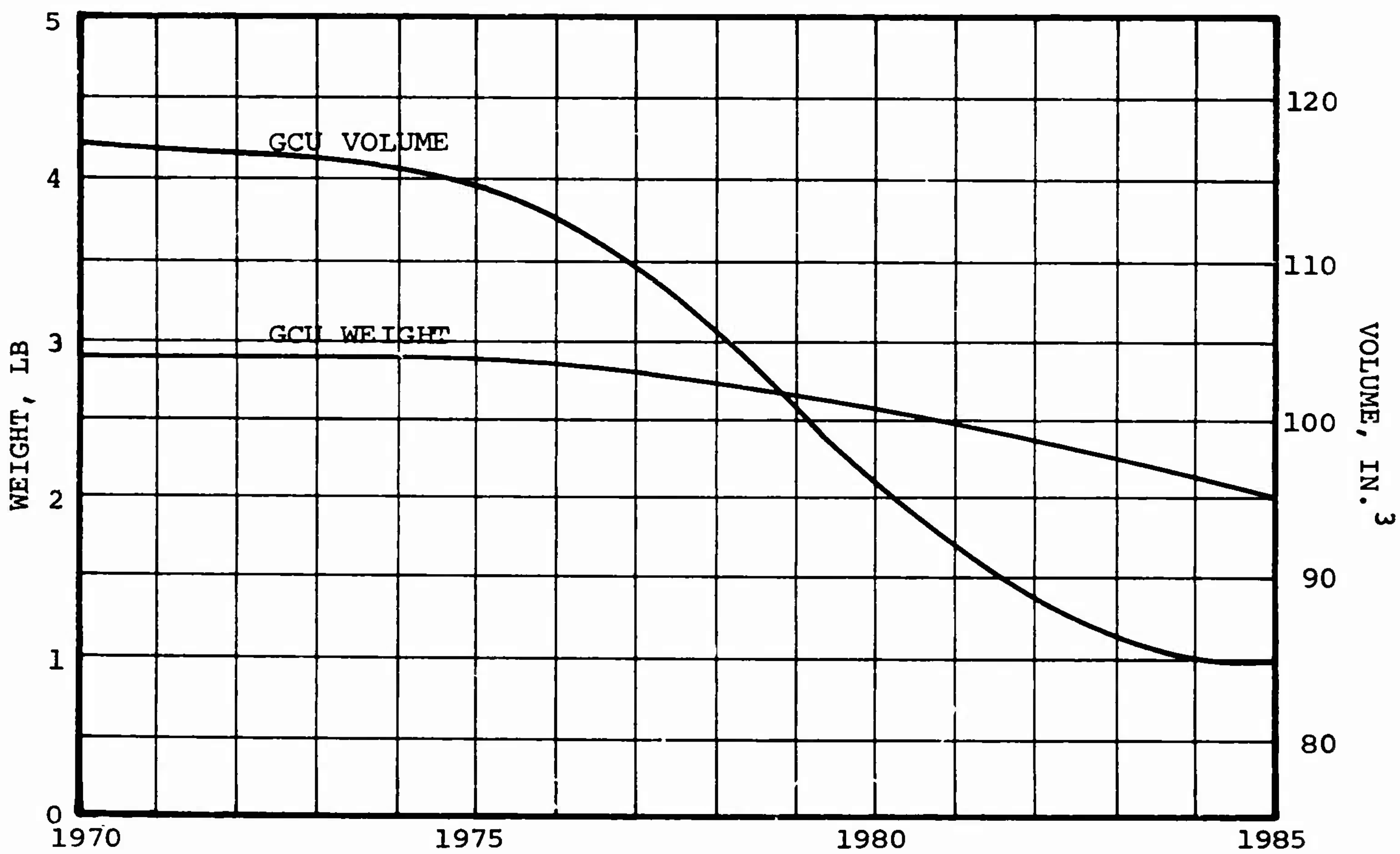

Figure 5. Generator Control Unit Weight and Volume Trends, 40-kva Rating.

The MTBF for the 400-Hz, 12,000-rpm generator and control unit and the system MMH/FH are shown in Figure 6. Predictions indicate the MTBF could be increased by 1985 with a corresponding decrease in maintainability, as shown on this curve.

This type of generator is available now and would, therefore, be applicable to all technology levels. The generator weight indicated in Table V represents a "three-quarter" configuration, i.e., the generator shaft is supported at the mounting end by the bearings in the gearbox mounting pad. Weight estimates for this type varied from 33 to 34 lb. These units are currently used in an Integrated Drive Generator (IDG) System, in which a constant speed drive is packaged with the generator. With a suitable mounting pad, this generator could be mounted on an accessory gearbox pad, which would support one end of the generator shaft. Cooling oil would be supplied from the gearbox. The weight of this generator in a complete two-bearing configuration would be about 39 lb.

The first type in Table V is the conventional four-pole, wound-rotor, oil-cooled 400-Hz system which currently exists and is shown for comparison, as is an air-cooled version of this same type of generator in a two-bearing design. A weight increase of about 20 percent is indicated. The next two types would also be capable of producing 400 Hz but at the increased speed of 24,000 rpm, which requires a new design for a two-pole, wound-rotor machine. Some weight decrease is estimated, but efficiency and MTBF are lower.

The solid rotor Lundell has good efficiency, MTBF, and TBO but weighs 110 lb and is considerably heavier than any other. All of the high-frequency generator systems require a converter to obtain 400-Hz power. In most current units designed for the rated output of the generator, the converter weight will approximate that of the generator. However, significant reductions are indicated by 1985.

The incorporation of a high-frequency generating system would require evaluation and design of the complete aircraft electrical system, to determine the overall effect of this approach. Since the necessary information was not available, these systems were not included in the study. Therefore, the 12,000-rpm, four-pole, wound-rotor unit was retained for the primary electrical generating system.

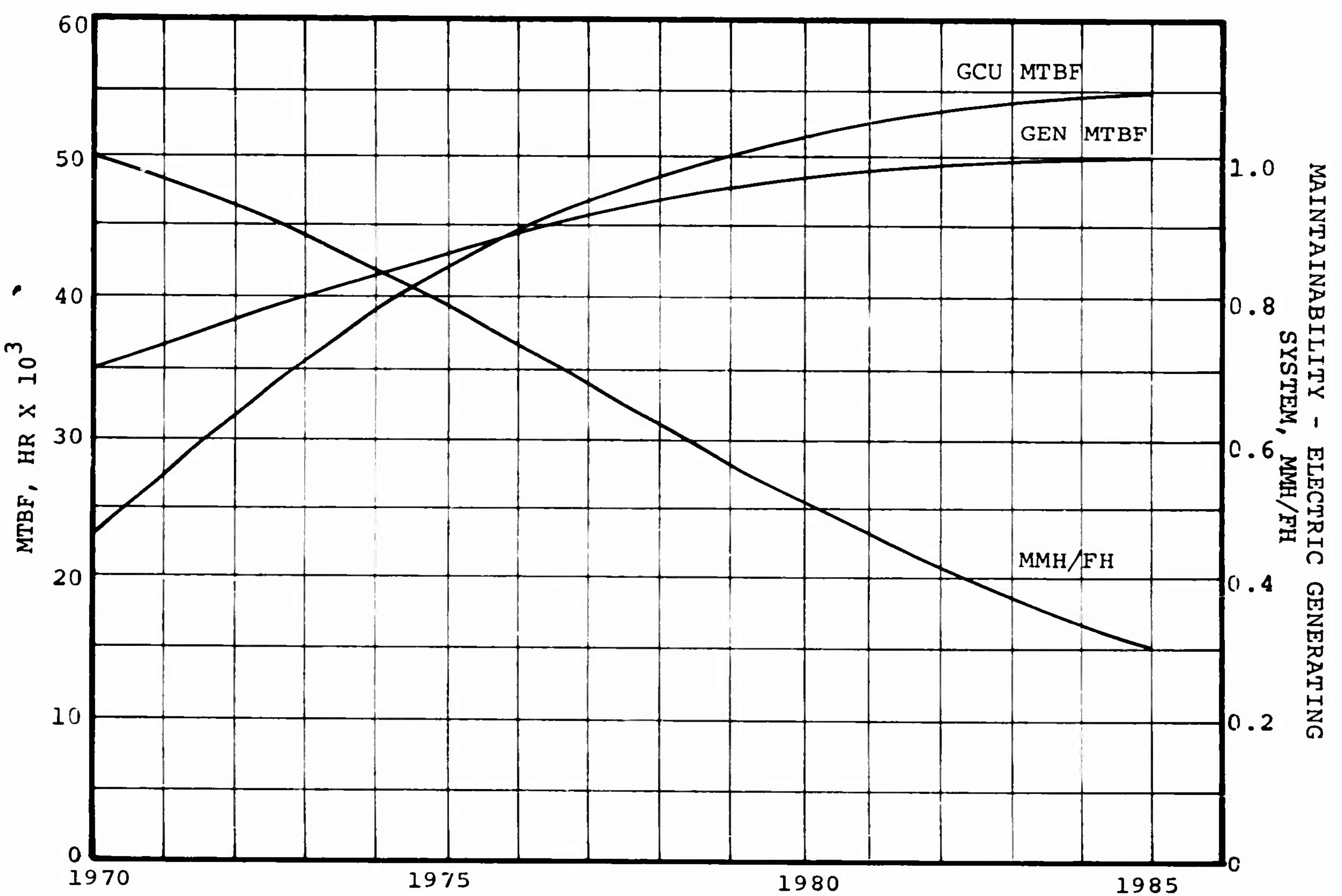

Figure 6. Reliability and Maintainability, 40-kva Electric Generating System.

TABLE V. ELECTRIC GENERATOR SUMM

Type	Cooling	Technology Level I Diameter (in.)	Length (in.)	Weight (lb)	Efficiency Rated Load (pct)	MTBF (hr)	TBO (hr)	Weight Change (pct)
12,000 rpm Wound Rotor, Oil-Cooled	4 gpm oil, 150°C maximum	6.96- 7.5	9.5	33- 34	83-85	20-35K	**	-10
12,000 rpm Wound Rotor, Air-Cooled, Four-Pole	Air blast 5 in. H_2O, 120°C maximum	7.3 - 7.5	10.0-10.5	41- 42	85 85	12-30K	**	-10
24,000 rpm, Wound Rotor, Oil-Cooled, Two-pole	4 gpm oil, 150°C maximum	6.3	9.5	27	76	15K	**	-10
24,000 rpm Wound Rotor, Air-Cooled, Two-pole	Air blast 5 in. H_2O, 120°C maximum	7.0	9.5	34	80	9K	**	-10
24,000 rpm Solid Rotor, Two-pole Lundell	Air blast or oil-cooled	11.0	8.0	110	86	20K	6000	-20
24,000 rpm Wound Rotor, Oil-Cooled VSCF	Oil	7.75	9.5	34	89	10K	**	-10
Converter for VSCF	Air or oil	-	-	37	95	20K	**	-14
64,000 rpm Solid Rotor, Four-Pole, Inductor	3 to 4 gpm oil, 150°C maximum	9.0	10.0	60	90	10K	15K	-10
Converter for 64,000 rpm Generator	Air blast	Volume 2000 in.^{3}		75	93	8K	6000	-30
60,000 rpm PMG with Samarium Cobalt (SmCo5) Four-Pole***	2 to 3 gpm oil, 150°C maximum	5.75	11.5	35	88	20K	15K	-20

*Costs based on production of 500/year minimum
**On condition
***Requires converter for 400-Hz power

LECTRIC GENERATOR SUMMARY 40-KVA RATING

	Technology Level III							Production Cost* Technology Level		
MTBF (hr)	TBO (hr)	Weight Change (pct)	Volume Change (pct)	Efficiency (pct)	MTBF (hr)	Development Cost (dollars)	I (dollars)	II (dollars)	III (dollars)
20-35K	**	-10	-10 to -15	89	50K	Normal Development	2000	1500-2500	1500-3000
12-30K	**	-10	-10 to -15	85	-	200K	2000	2500	3000
15K	**	-10	-10 to -15	85	30K	200K	2000	2500	3000
9K	**	-10	-10 to -15	85	30K	200K	2000	2500	3000
20K	6000	-20	-25	-	-	300K	2000	2500	3000
10K	**	-10	-6	89	12K	-	-	5000	4000
20K	**	-14	-	95	25K	-	1000	-	9000
10K	15K	-10	15	90	30K	200K	2000	2500	3000
8K	6000	-30	30	-	-	500K	13K	15K	18K
20K	15K	-20	20	-	-	200K	2000	2500	3000

4. CANDIDATE SYSTEM SELECTION

The basic potential candidate systems for the subject program are identified by system identification keys (Figure 7). These keys utilize the matrixes (Figures 8 and 9) to identify a system by its power path from the APU to the accessory gearbox and to the main engine (starting). The first number of the key represents the APU arrangement in the system; i.e., remotely mounted or mounted directly on the accessory gearbox. The second number is the power link from the APU to the gearbox; the third, the link from the gearbox to the main engine; and the fourth, the link from the APU to the main engine. If no link occurs in some portion of a system, this is represented by a zero.

The identifiable basic systems are listed on Table VI and their schematics are shown in Figures 10 through 36. To these basic schemes, the variations and trade-offs can then be added.

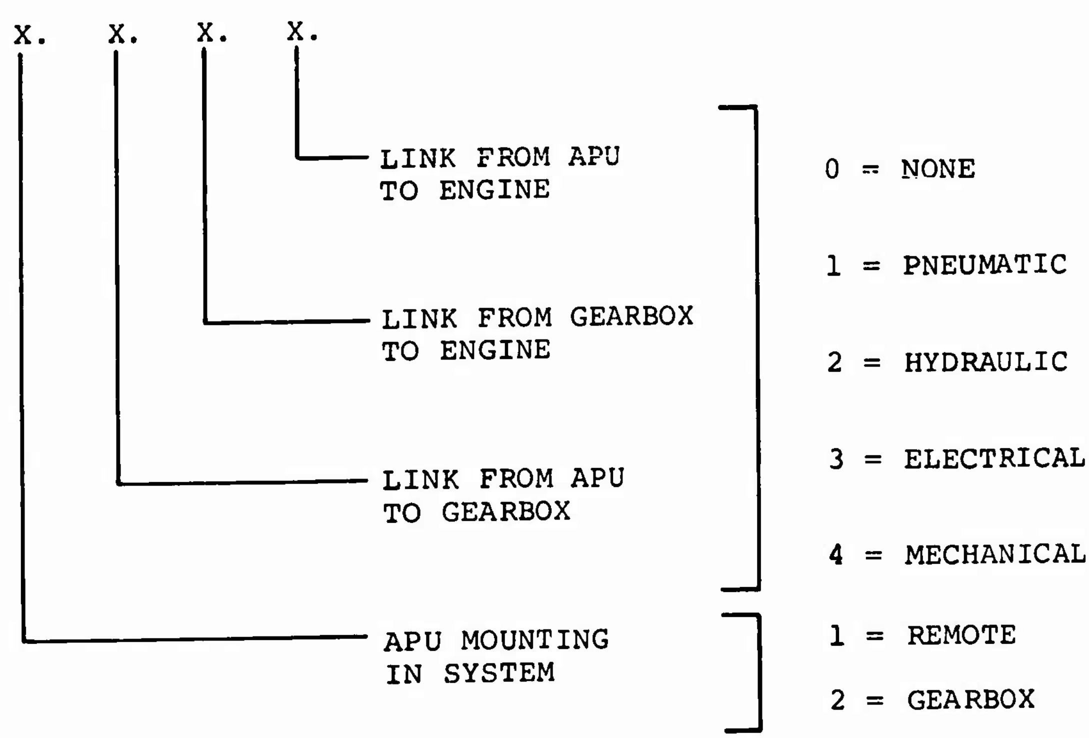

Figure 7. System Identification Key.

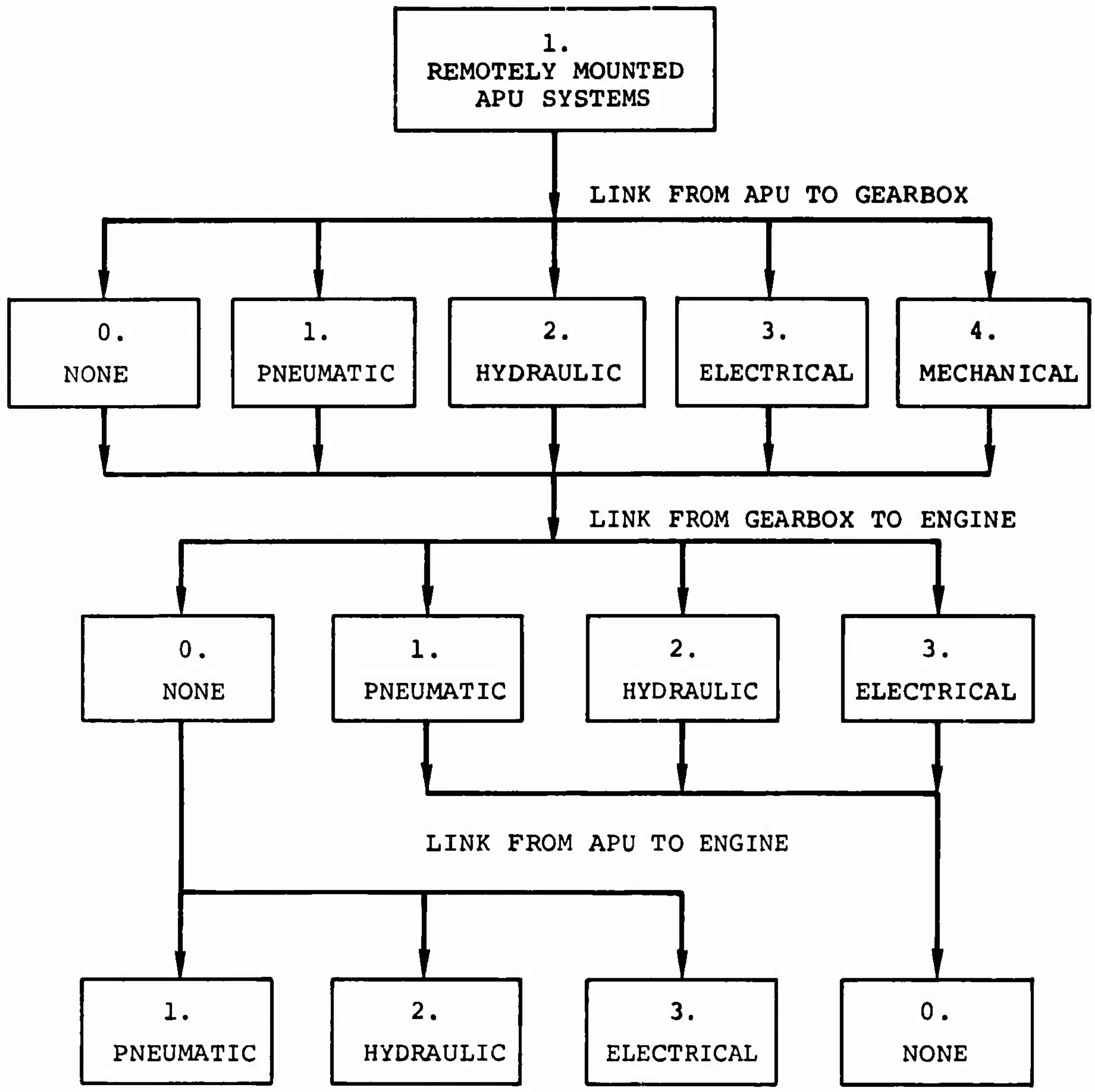

Figure 8. System Identification Numbering Schematic, Remotely Mounted APU Systems.

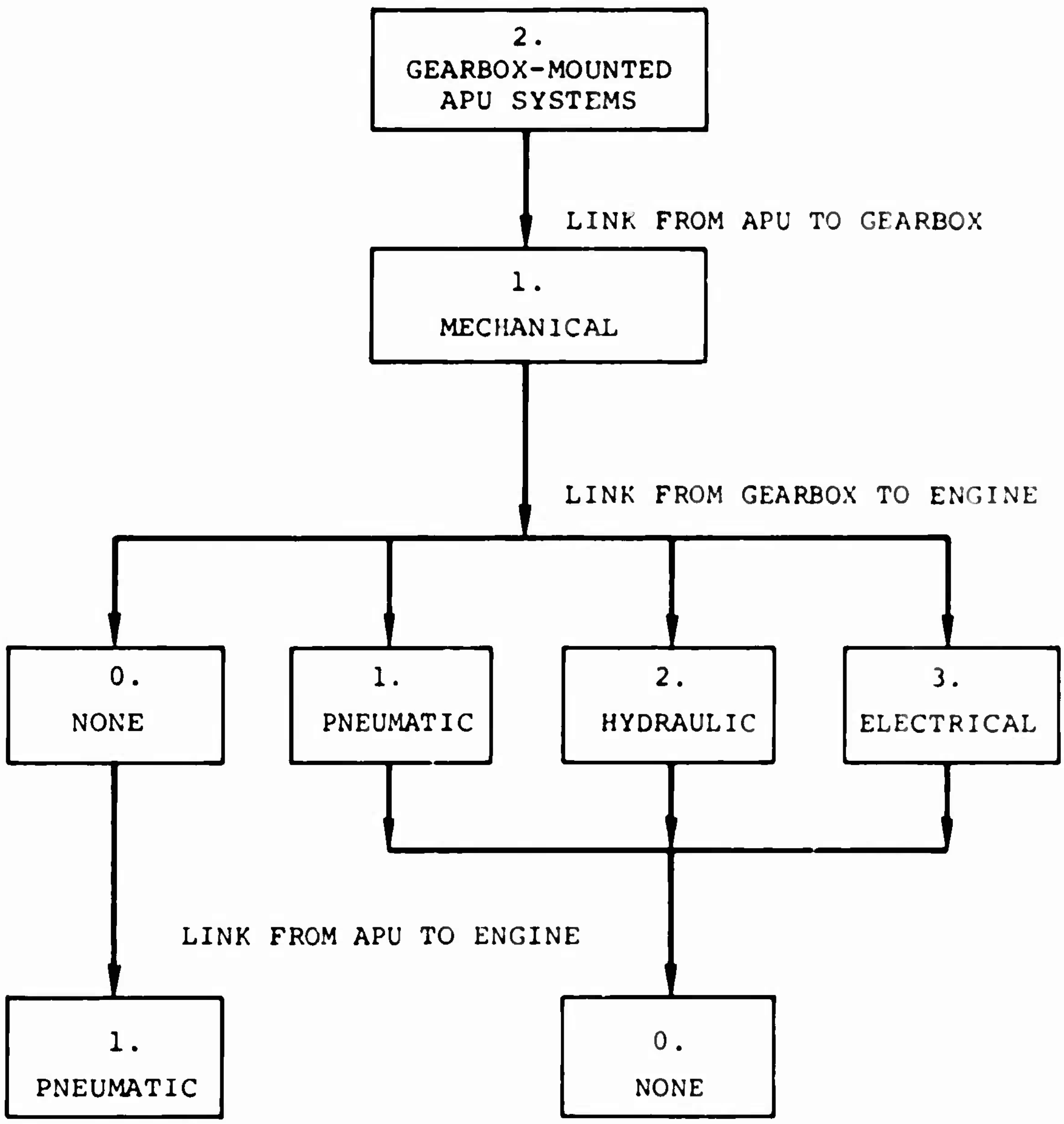

Figure 9. System Identification Numbering Schematic, Gearbox-Mounted APU Systems.

TABLE VI. CANDIDATE SYSTEMS

1. Remote APU Systems

   1.0 No Link to Accessory Gearbox

      1.0.0.1 Pneumatic Link to Engine from APU
      1.0.0.2 Hydraulic Link to Engine from APU
      1.0.0.3 Electric Link to Engine from APU

   1.1 Pneumatic Link to Accessory Gearbox

      1.1.1.0 Pneumatic Link to Engine from Gearbox
      1.1.2.0 Hydraulic Link to Engine from Gearbox
      1.1.3.0 Electric Link to Engine from Gearbox
      1.1.0.1 Pneumatic Link to Engine from APU
      1.1.0.2 Hydraulic Link to Engine from APU
      1.1.0.3 Electric Link to Engine from APU

   1.2 Hydraulic Link to Accessory Gearbox

      1.2.1.0 Pneumatic Link to Engine from Gearbox
      1.2.2.0 Hydraulic Link to Engine from Gearbox
      1.2.3.0 Electric Link to Engine from Gearbox
      1.2.0.1 Pneumatic Link to Engine from APU
      1.2.0.2 Hydraulic Link to Engine from APU
      1.2.0.3 Electric Link to Engine from APU

   1.3 Electric Link to Accessory Gearbox

      1.3.1.0 Pneumatic Link to Engine from Gearbox
      1.3.2.0 Hydraulic Link to Engine from Gearbox
      1.3.3.0 Electric Link to Engine from Gearbox
      1.3.0.1 Pneumatic Link to Engine from APU

   1.4 Mechanical Link to Accessory Gearbox

      1.4.1.0 Pneumatic Link to Engine from Gearbox
      1.4.2.0 Hydraulic Link to Engine from Gearbox
      1.4.3.0 Electric Link to Engine from Gearbox
      1.4.0.1 Pneumatic Link to Engine from APU

2. Gearbox-Mounted APU

   2.1 Mechanical Link to Accessory Gearbox

      2.4.1.0 Pneumatic Link to Engine from Gearbox
      2.4.2.0 Hydraulic Link to Engine from Gearbox
      2.4.3.0 Electric Link to Engine from Gearbox
      2.4.0.1 Pneumatic Link to Engine from APU

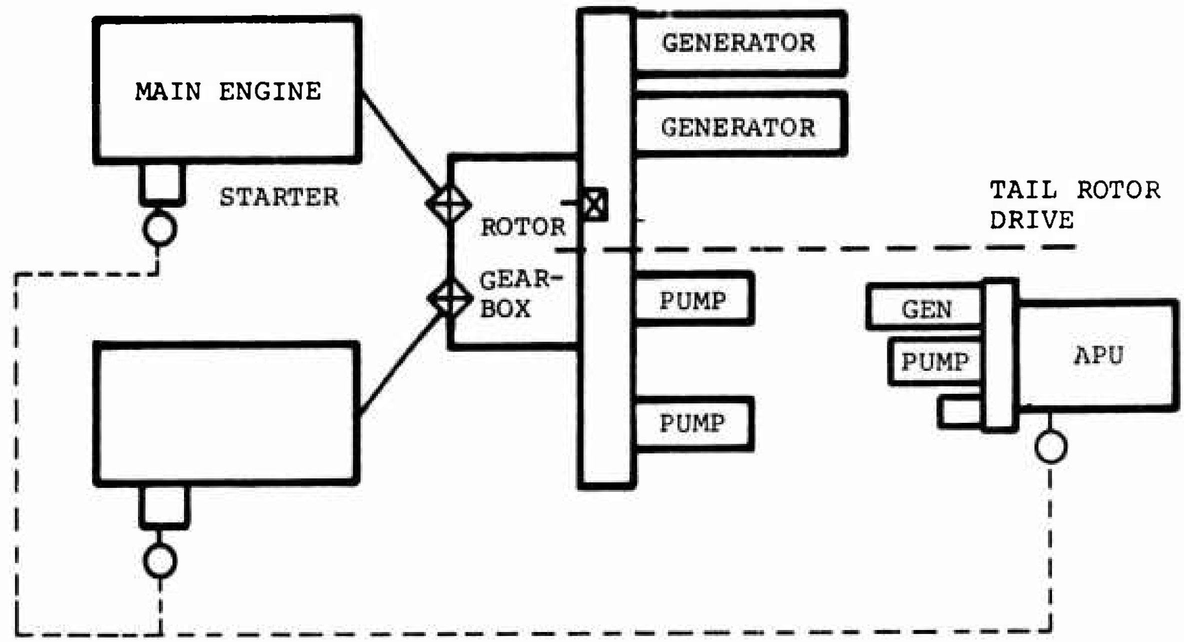

Figure 10. System 1.0.0.1.

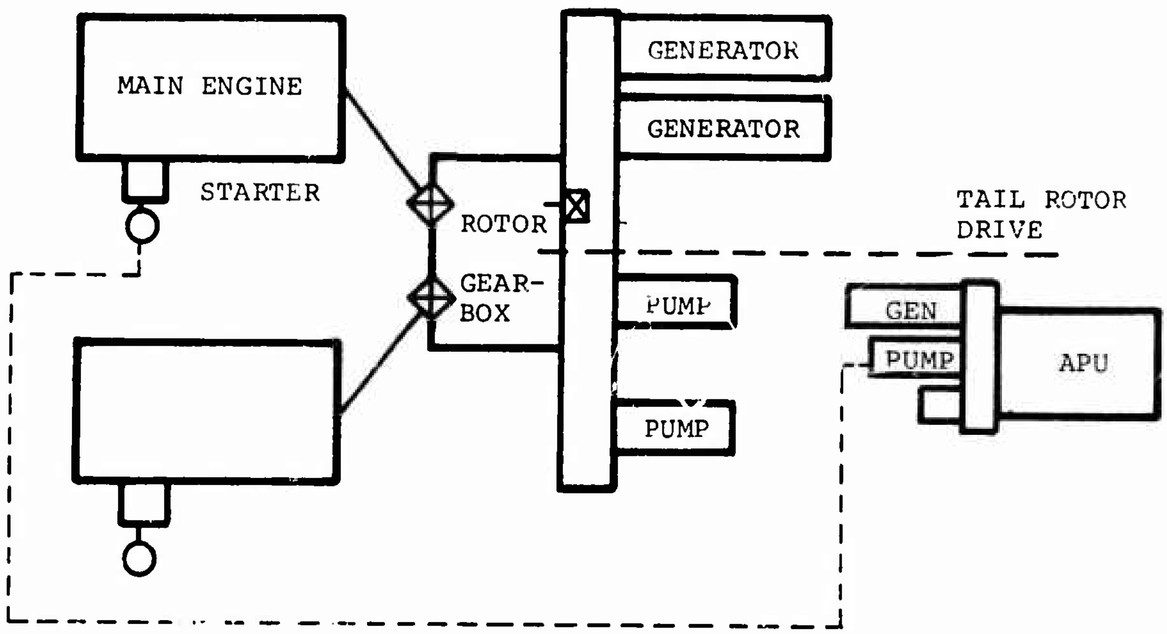

Figure 11. System 1.0.0.2.

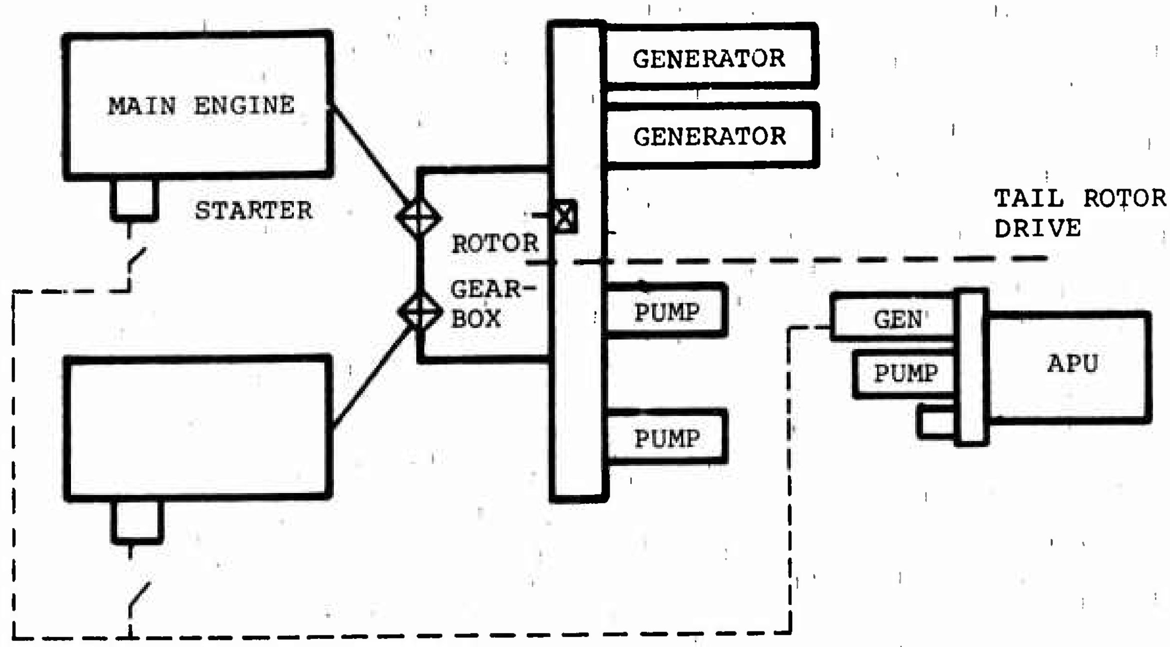

Figure 12. System 1.0.0.3.

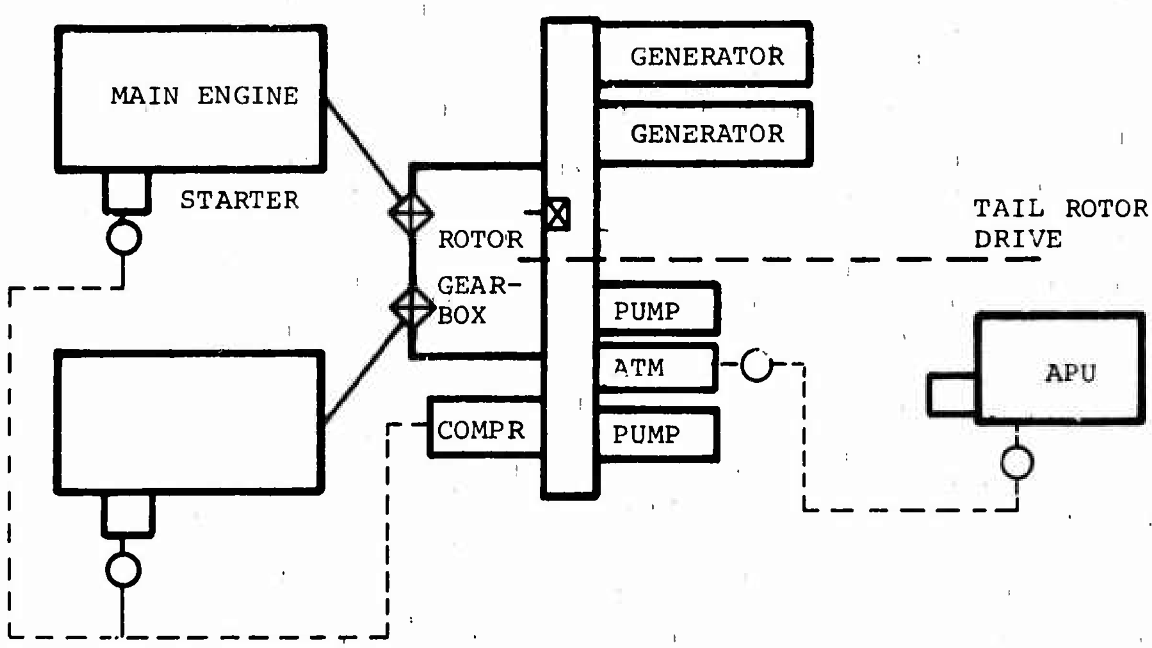

Figure 13. System 1.1.1.0.

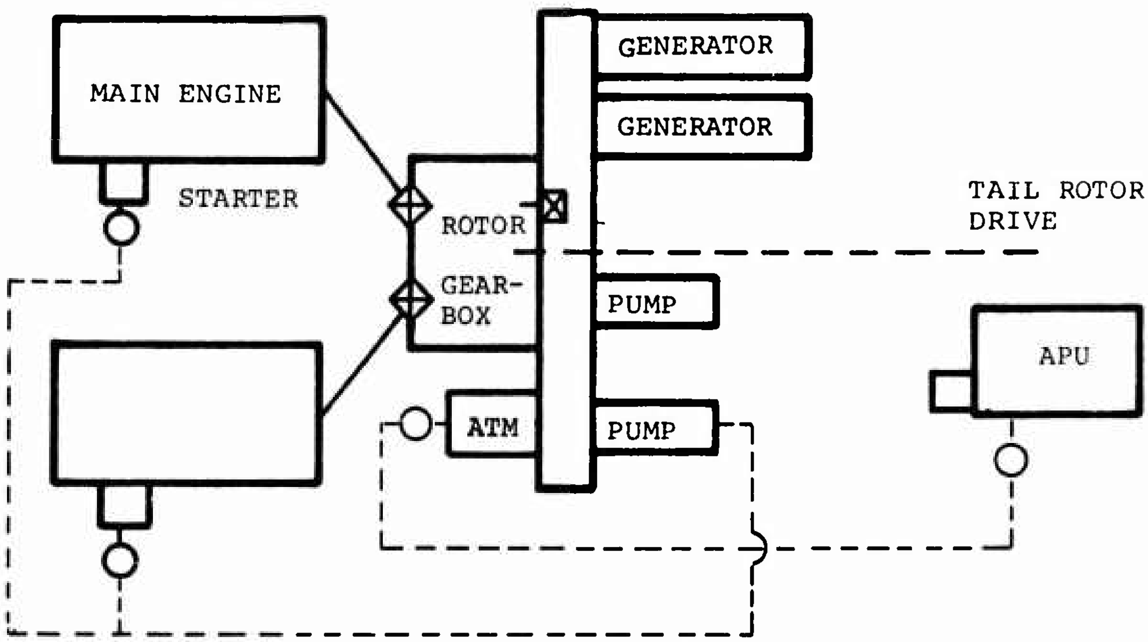

Figure 14. System 1.1.2.0.

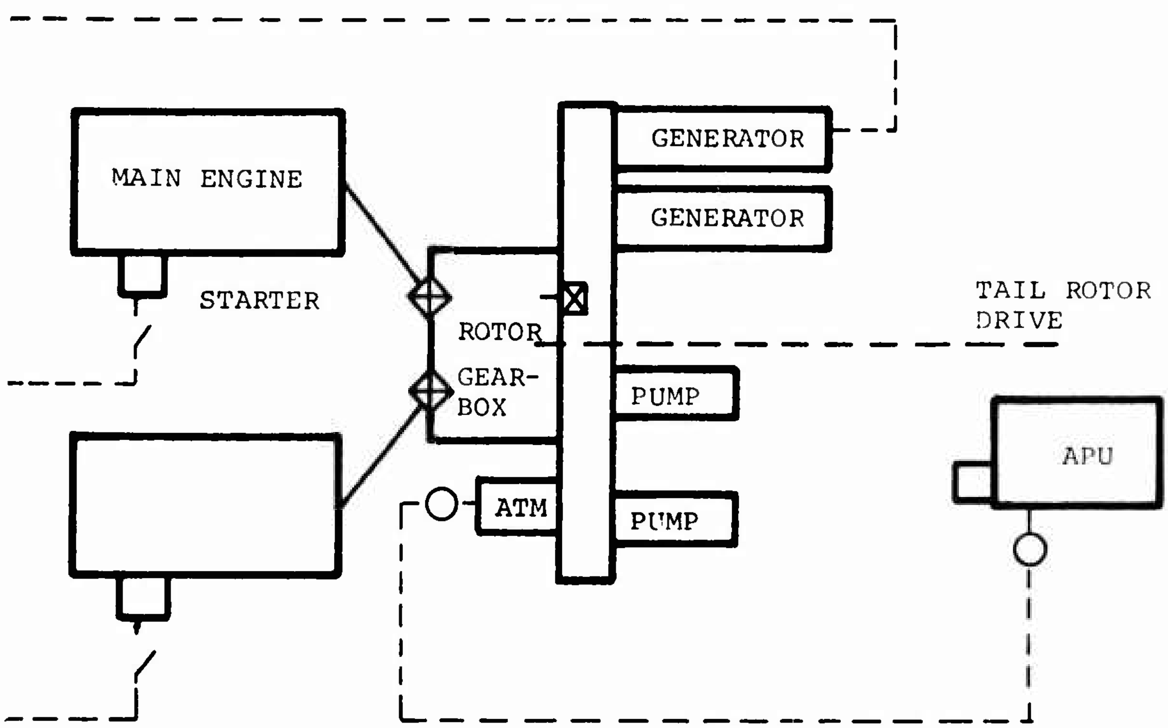

Figure 15. System 1.1.3.0.

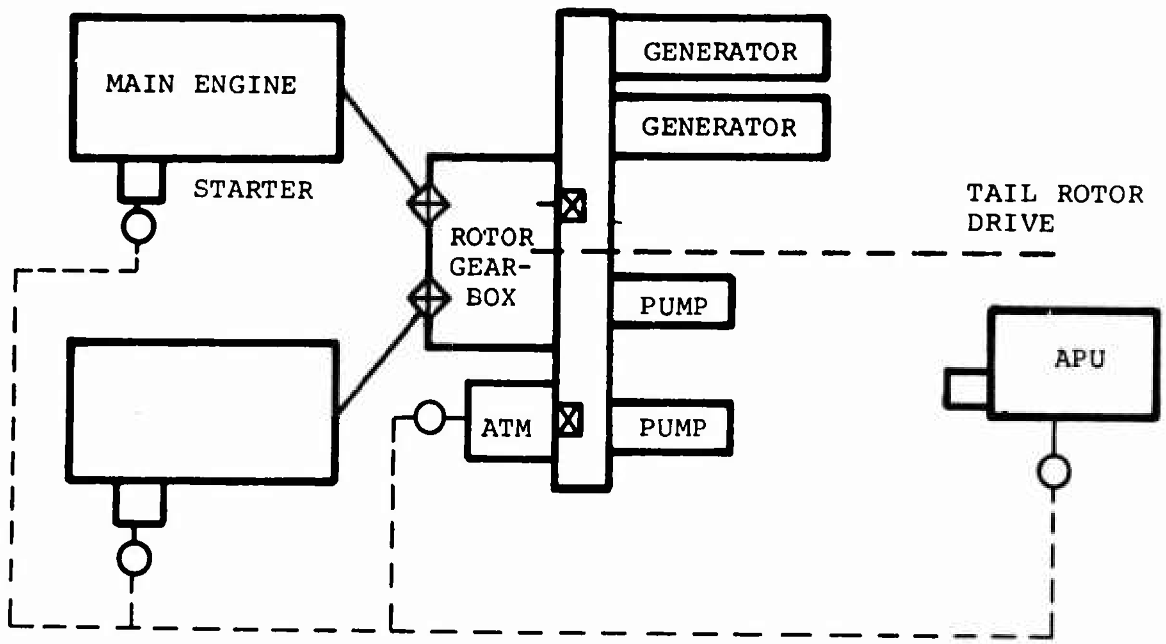

Figure 16. System 1.1.0.1.

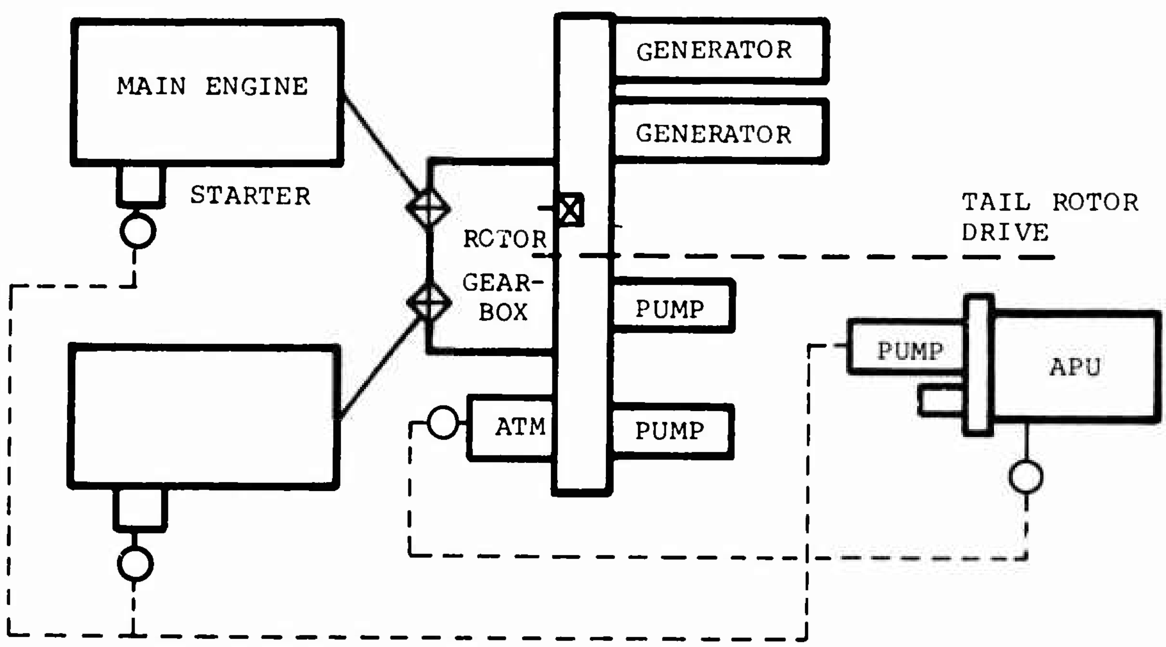

Figure 17. System 1.1.0.2.

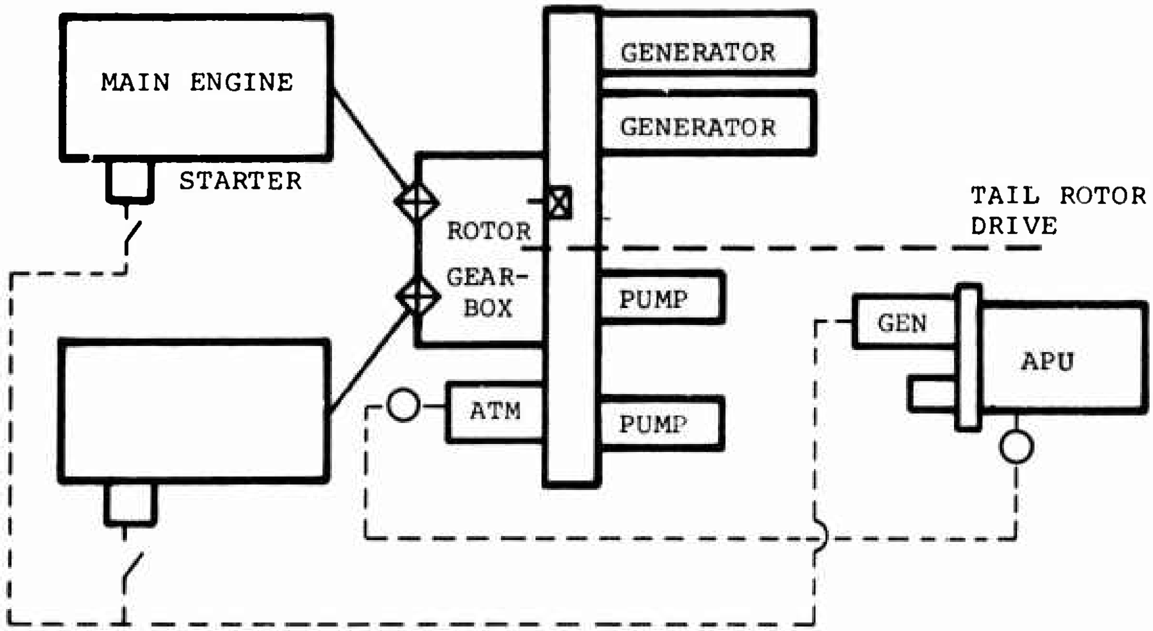

Figure 18. System 1.1.0.3.

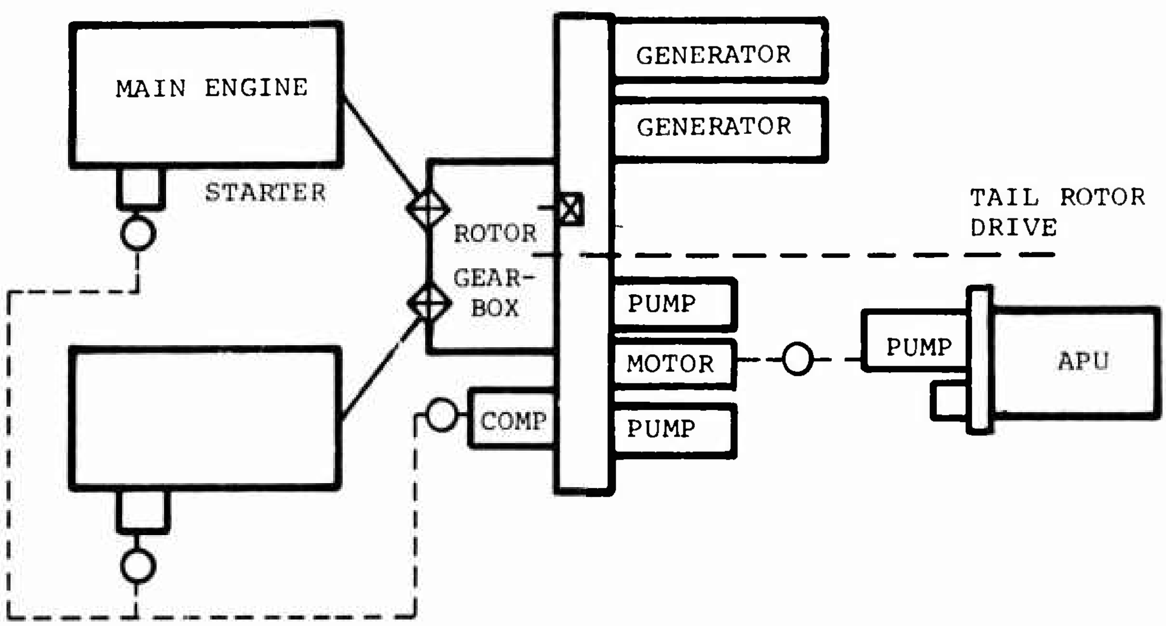

Figure 19. System 1.2.1.0.

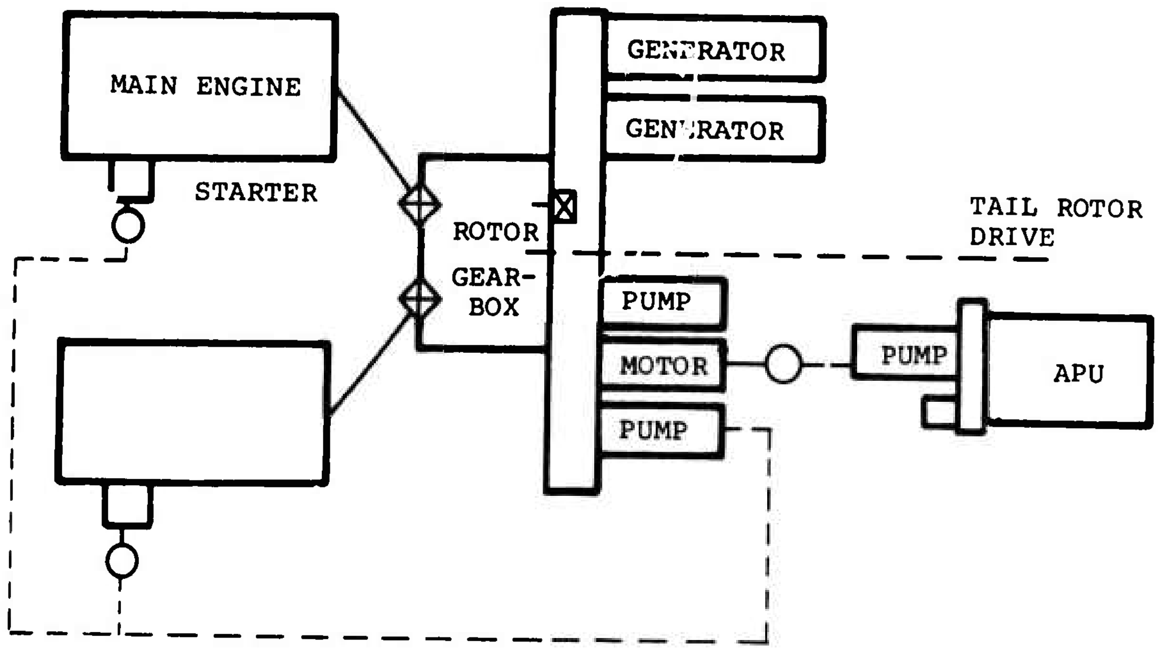

Figure 20. System 1.2.2.0.

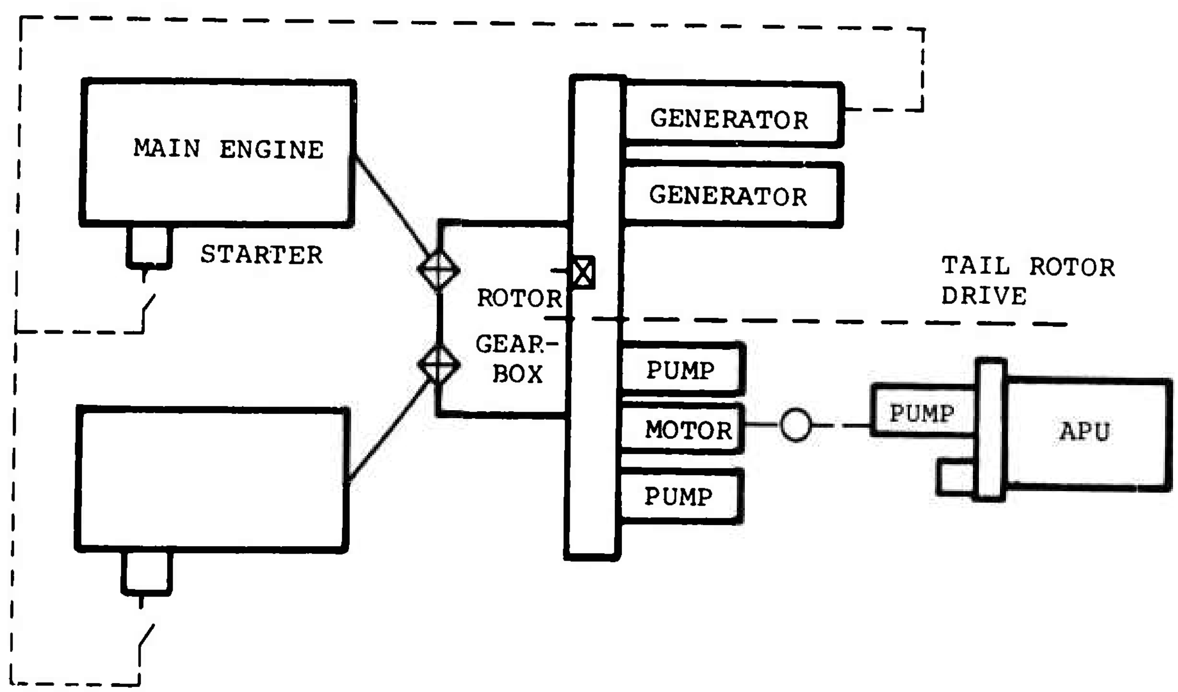

Figure 21. System 1.2.3.0.

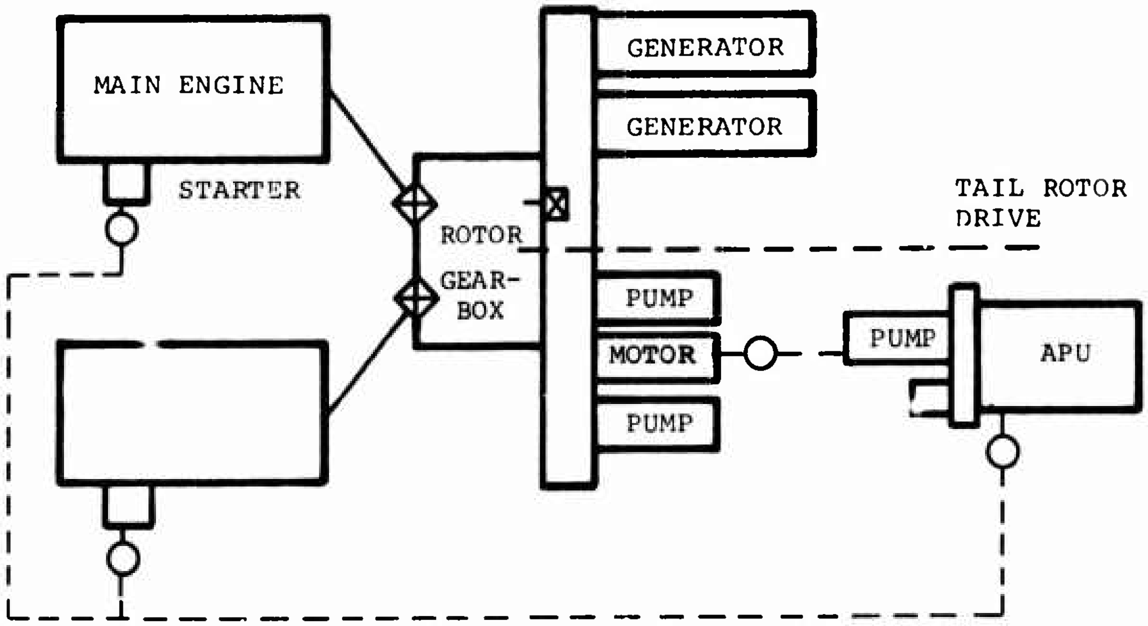

Figure 22. System 1.2.0.1.

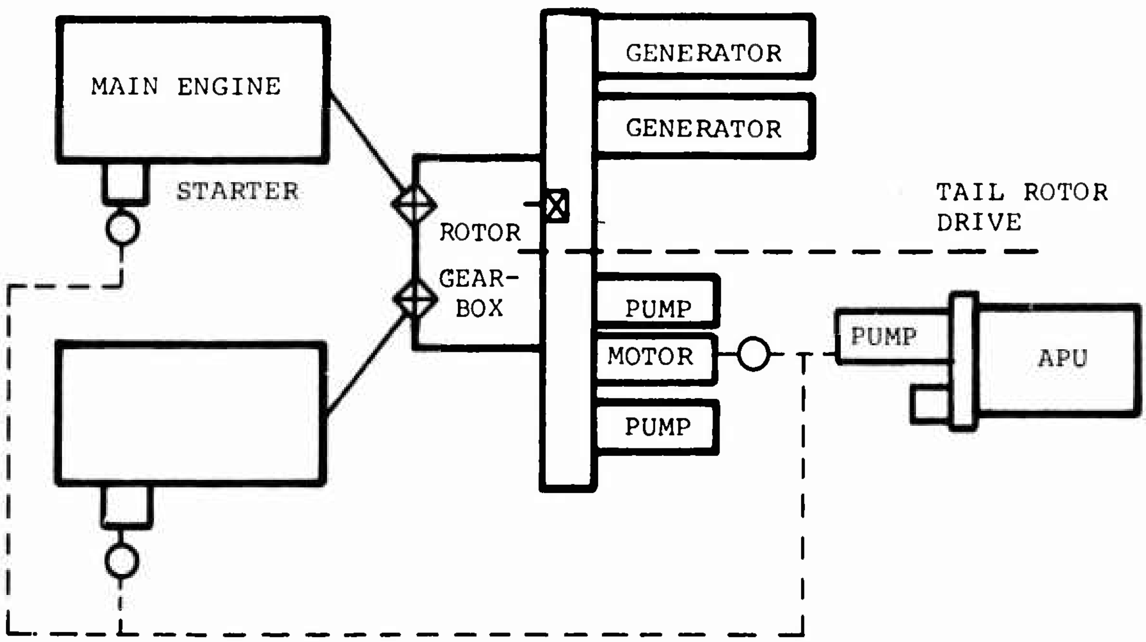

Figure 23. System 1.,2.0.2.

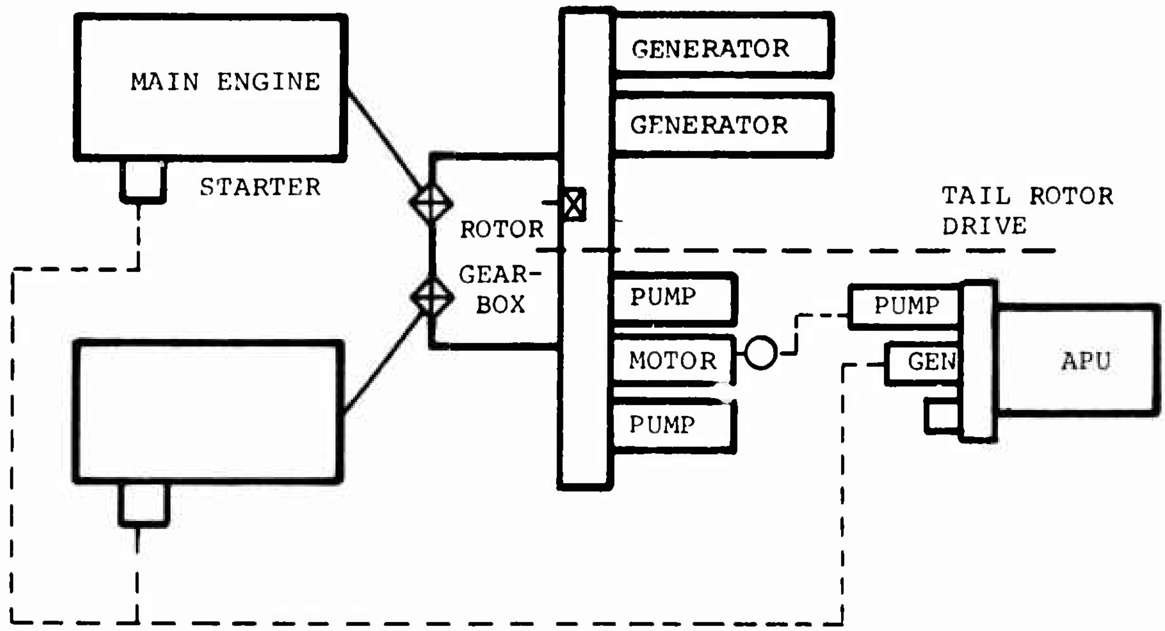

Figure 24. System 1.2.0.3.

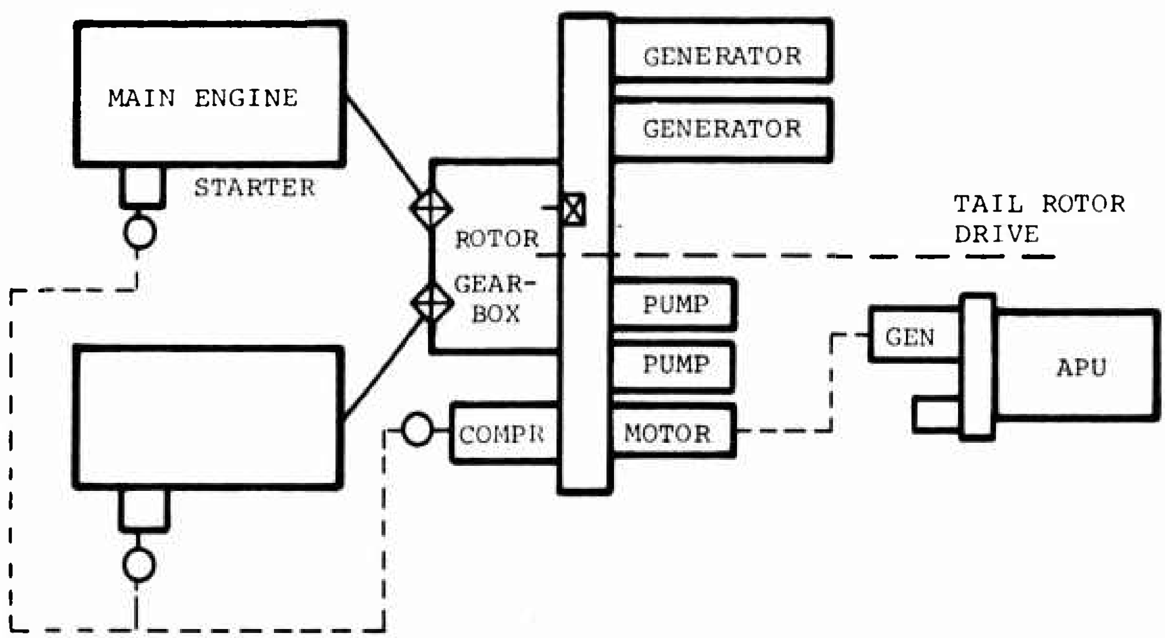

Figure 25. System 1.3.1.0.

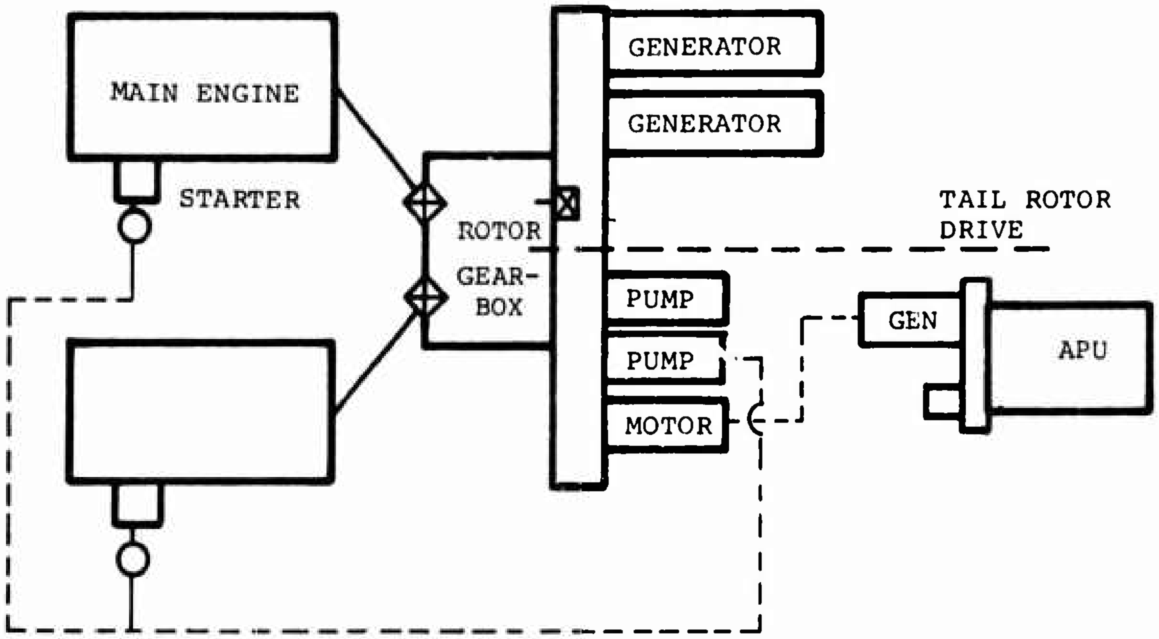

Figure 26. System 1.3.2.0.

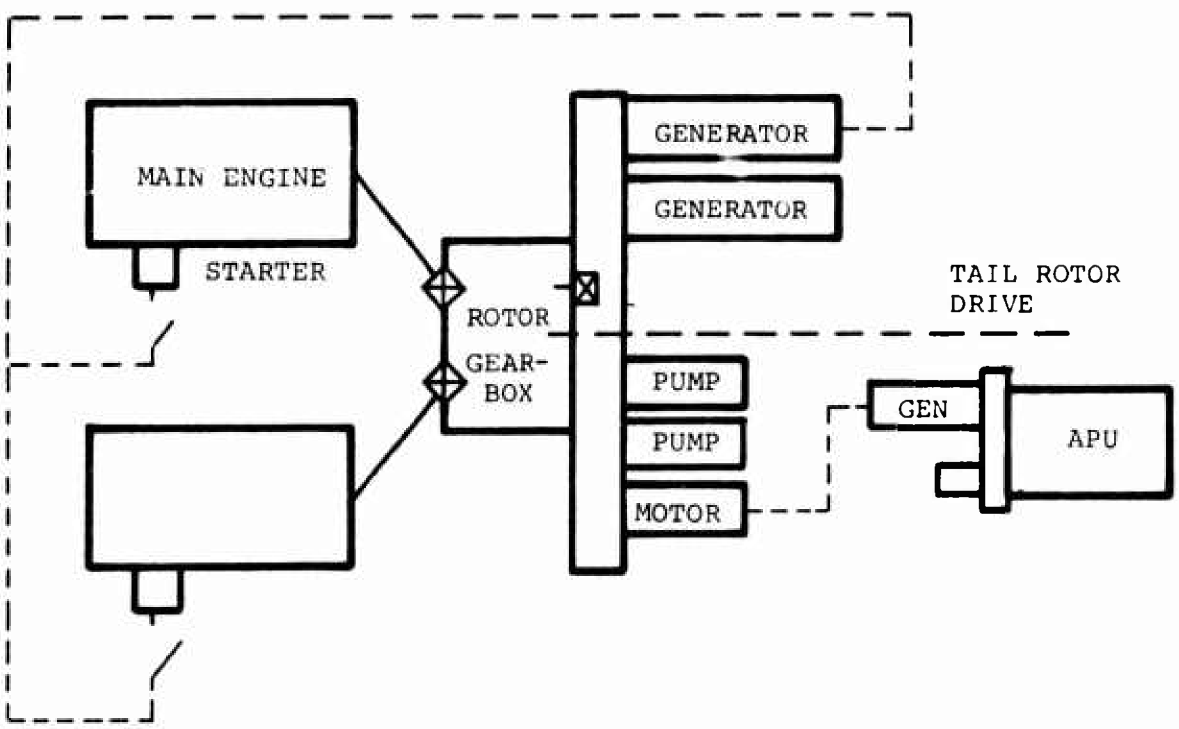

Figure 27. System 1.3.3.0.

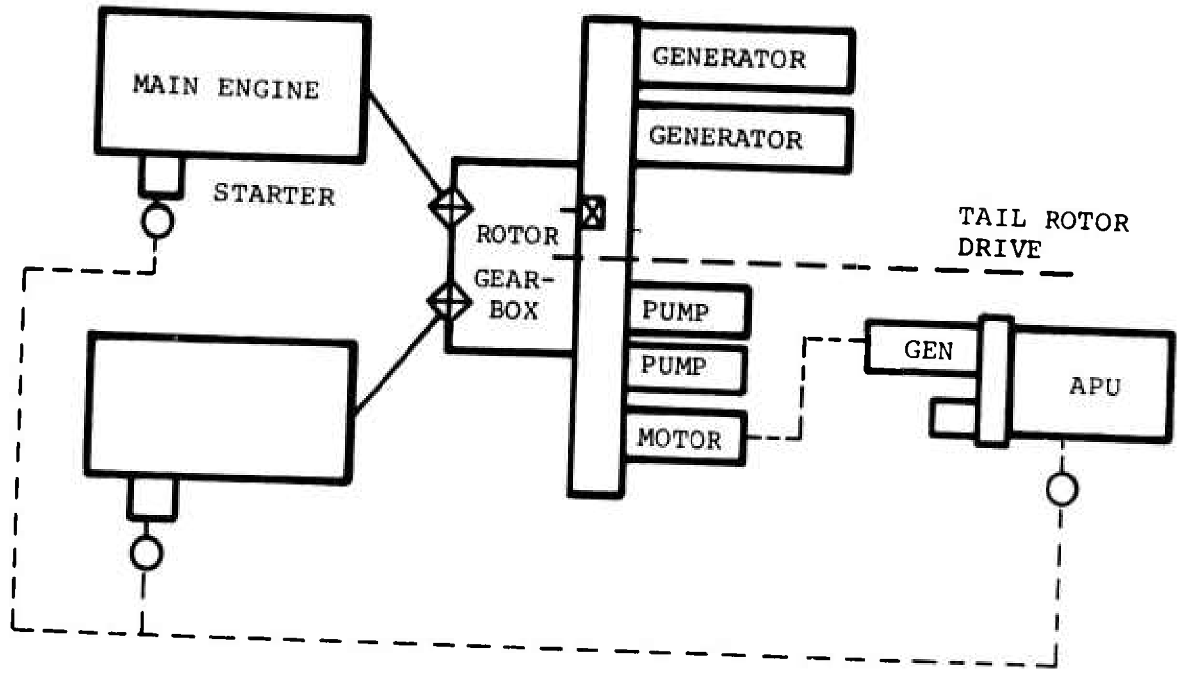

Figure 28. System 1.3.0.1.

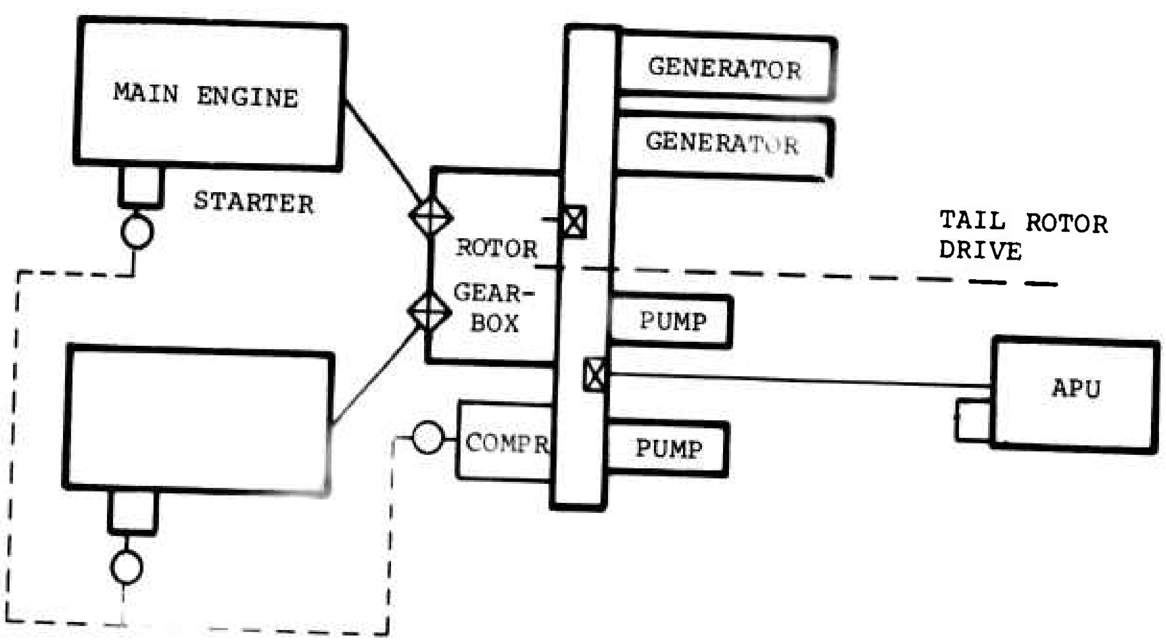

Figure 29. System 1.4.1.0.

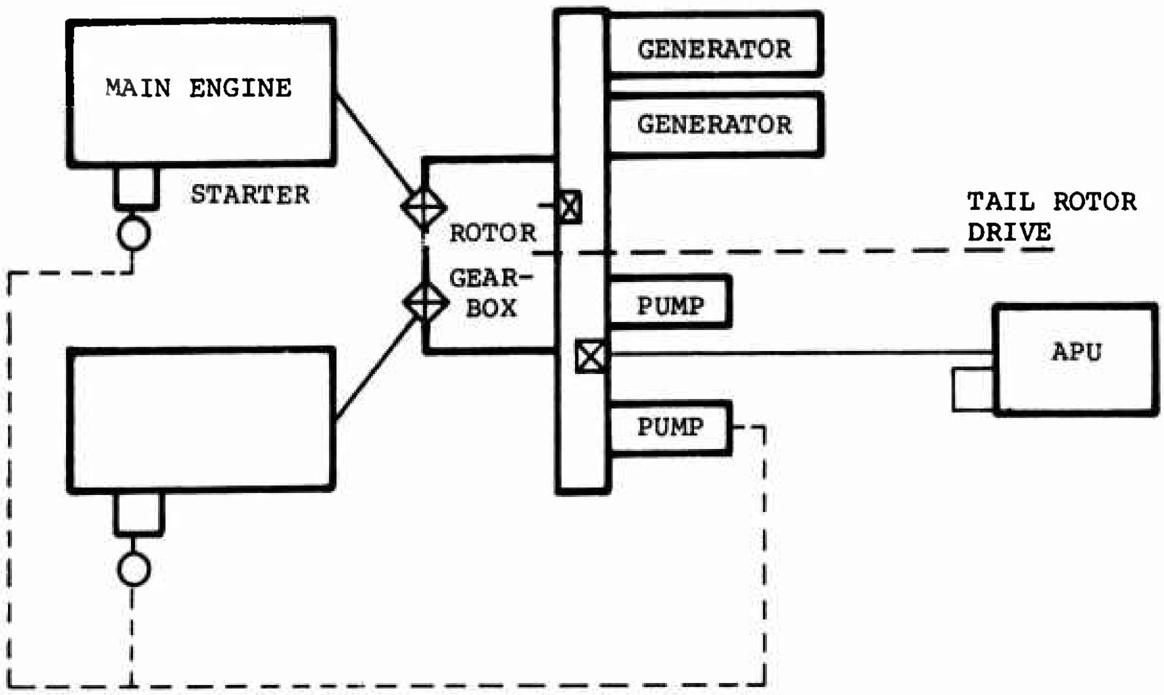

Figure 30. System 1.4.2.0.

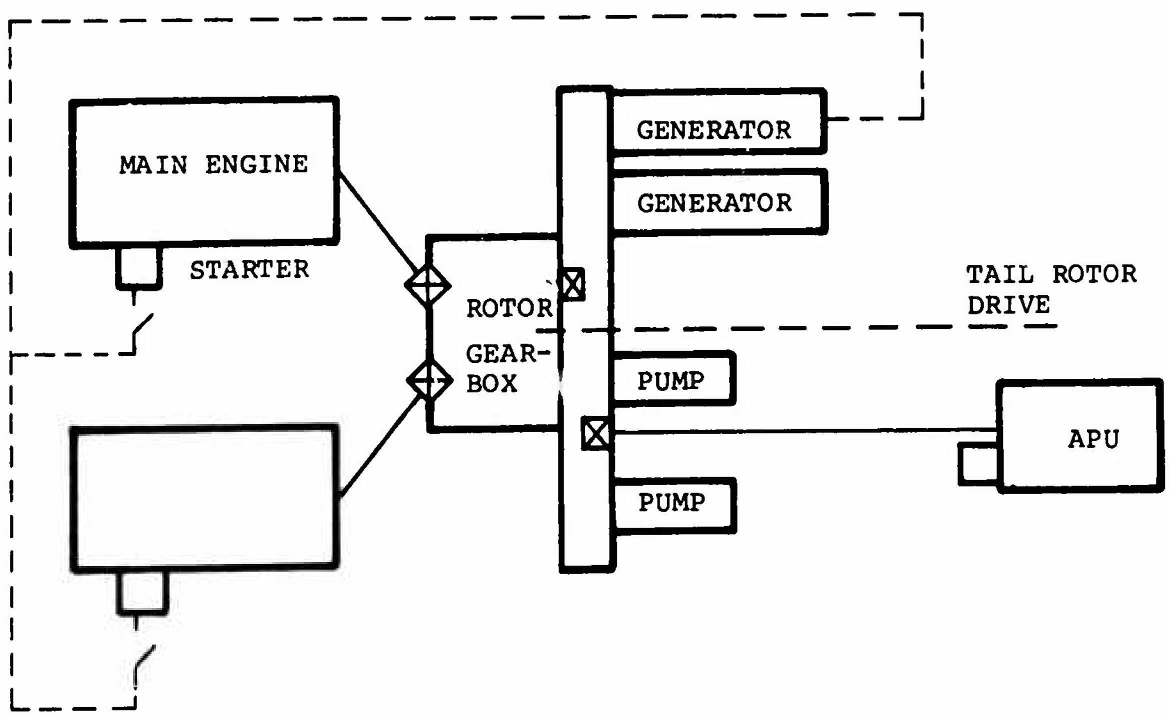

Figure 31. System 1.4.3.0.

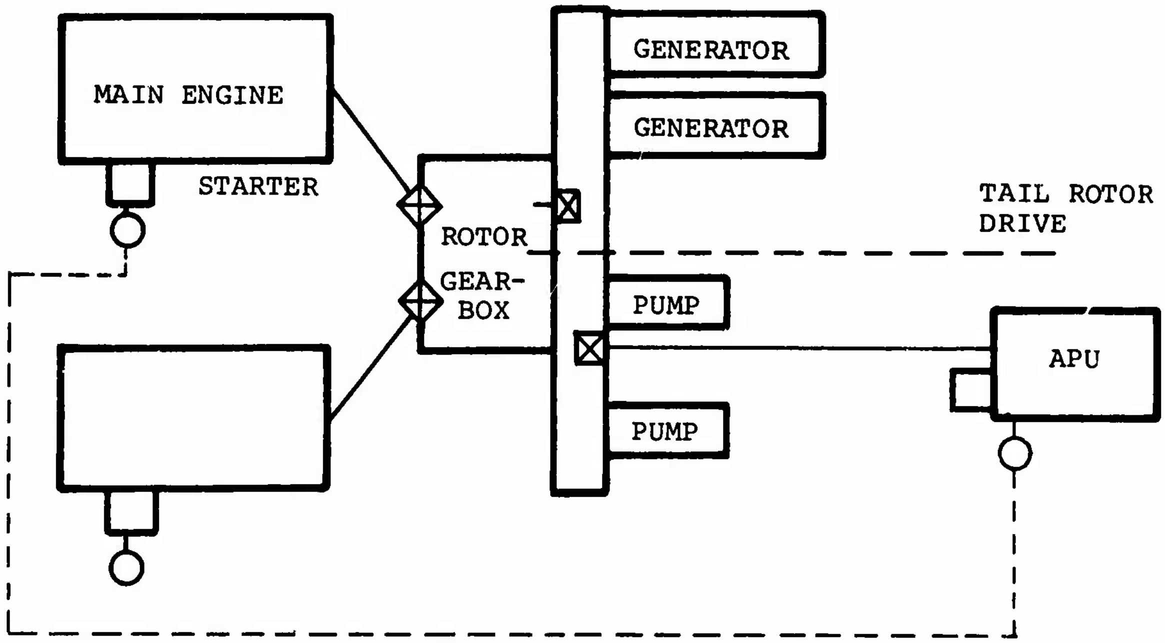

Figure 32. System 1.4.0.1.

The principal variation of all systems is the addition of an ECS. The systems, as shown in the sketches, employ ventilating fans for avionics and cockpit cooling, as well as a ventilating fan for the cabin. The ECS can be either an air or vapor cycle. Other systems will include APU variations (i.e., single-shaft, free-turbine, two-spool, integral-bleed, load-compressor, etc.); APU sized for altitude operation; generator and/or electrical equipment variations for dc loads and electrical engine starting; hydraulic pumps sized for engine starting; motor-pump combinations; the addition of driven compressors to the gearbox; APU starting systems; and redundant main engine starting systems. Systems that do not include an air-cycle ECS will generally require another type of heating for the cockpit and cabin.

Once the basic systems and variations were established, the components were identified and the performance was calculated for the power links in the various operating modes. All power requirements were then referenced to the APU for sizing, and the basic SPS components were resized, as required.

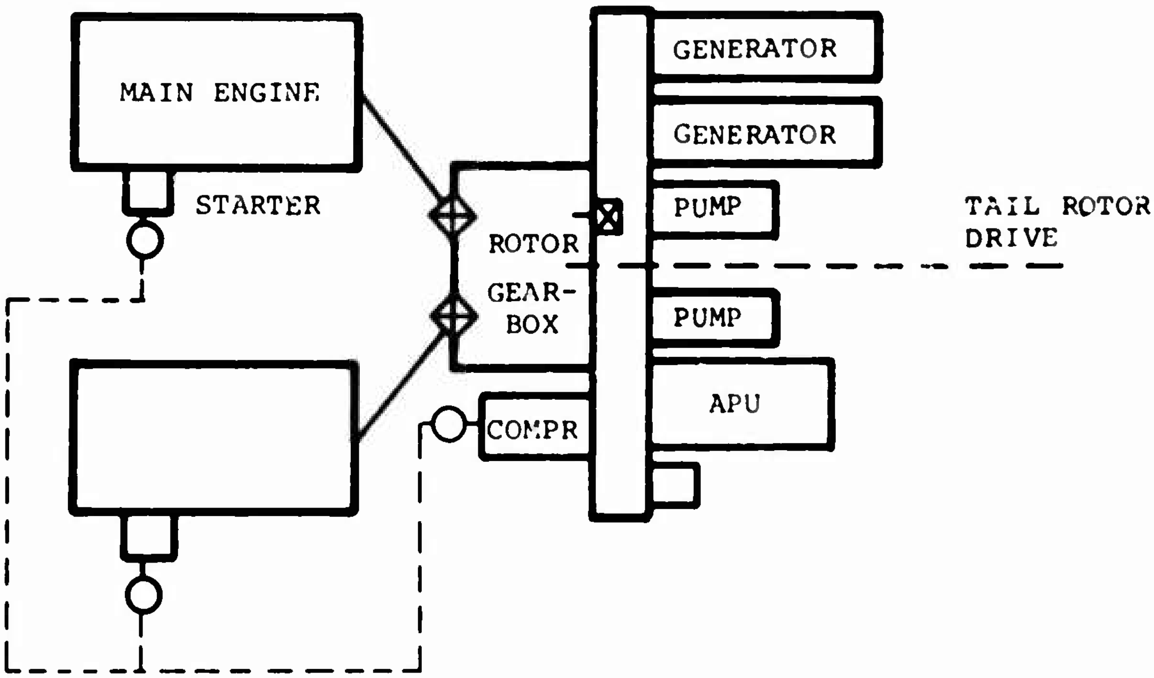

Figure 33. System 2.4.1.0.

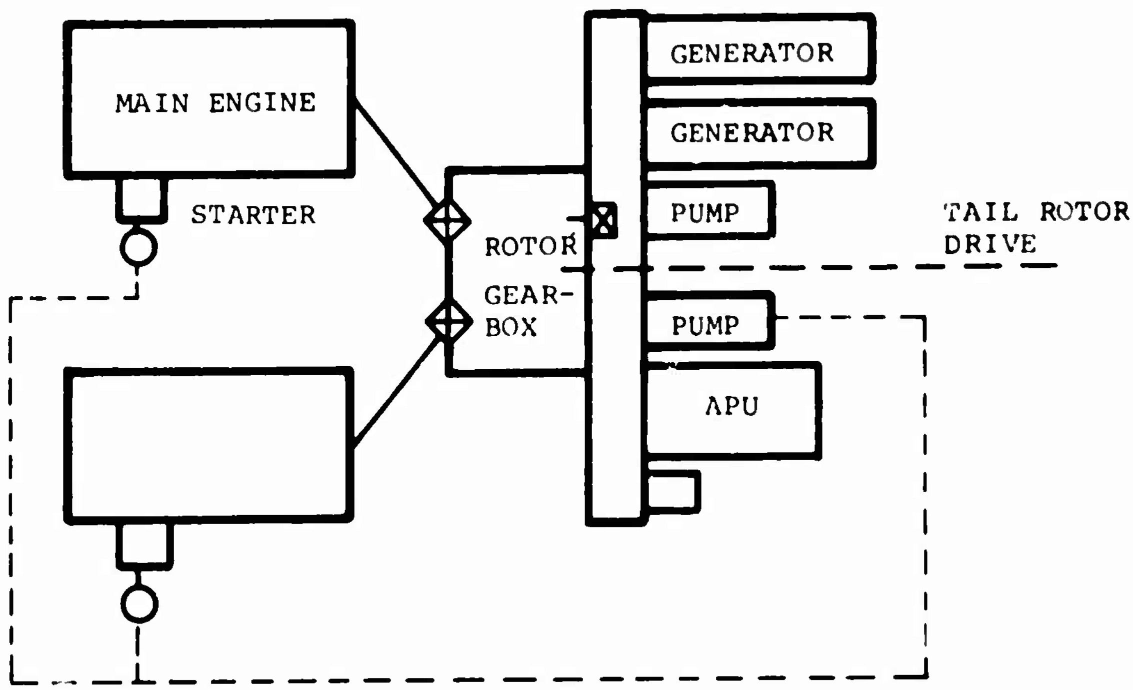

Figure 34. System 2.4.2.0.

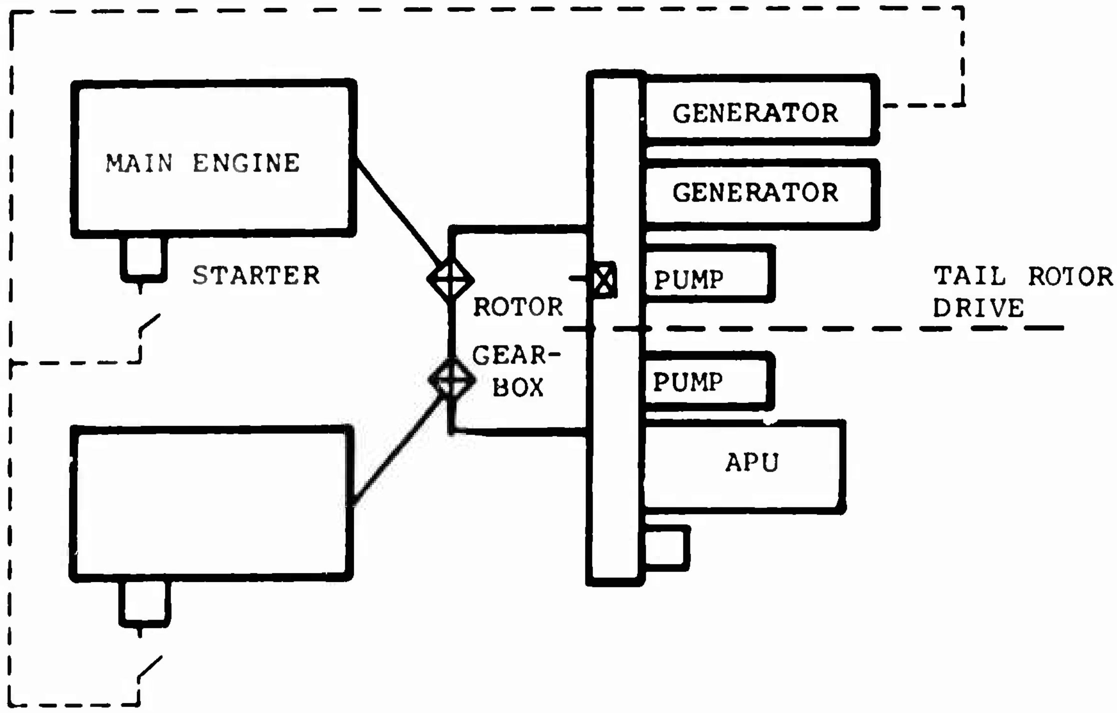

Figure 35. System 2.4.3.0.

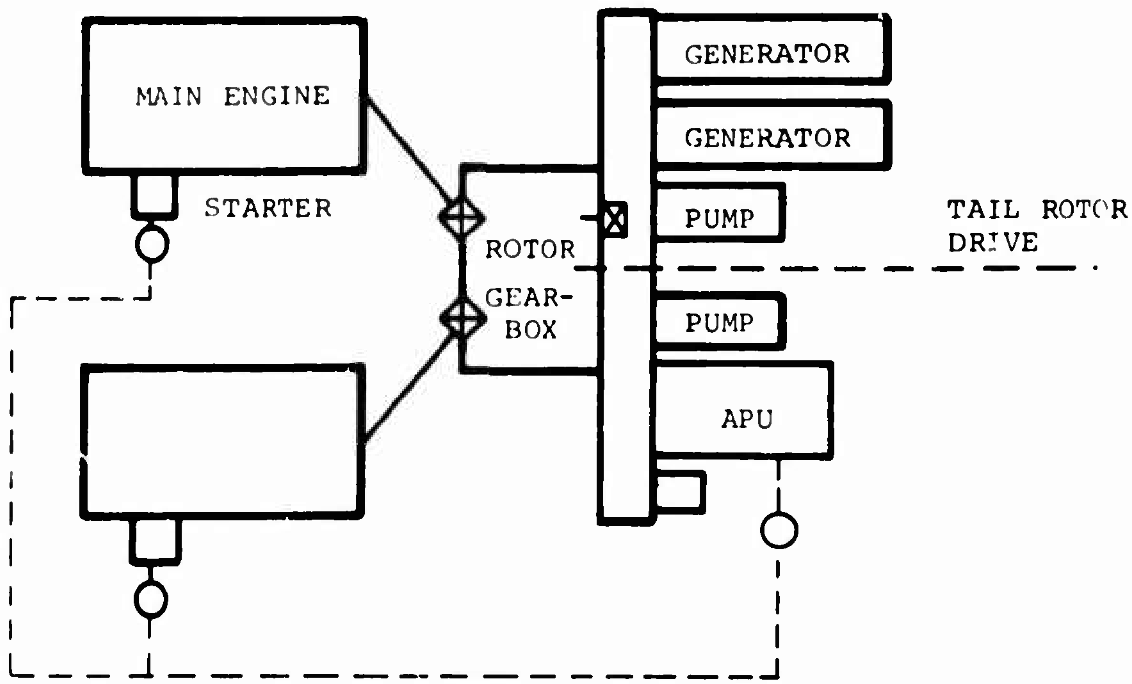

Figure 36. System 2.4.0.1.

5. AIRCRAFT MISSION AND SYSTEM POWER REQUIREMENTS

5.1 AIRCRAFT MISSION

The primary aircraft mission and power requirements of this study consisted of the basic elements derived from the survey data, with slight adjustments in power to account for ventilating loads and for the addition of an ECS to the basic systems. Table VII defines the mission for which all systems were evaluated.

Basic systems included components requiring 1 kva additional power for ventilation cooling the avionic compartment, the cockpit, and the cabin. This same power was required in systems that included the optional ECS to provide positive cooling airflow from the refrigeration package through the avionics compartment and for ventilation cooling the cabin.

The mission analysis was conducted at hot-day conditions to analyze the systems with the proper APU and ECS size.

This primary mission was the basis for system comparisons. Selected systems were compared by modifying the power source to evaluate the APU operating in flight and, when systems contained gearbox-mounted compressors, to compare the effect of engine bleed versus shaft power for ECS.

5.2 SYSTEM POWER REQUIREMENTS

The power requirements for each candidate system were established by summing all component power in a particular operating mode and referencing this power to the required source (APU or main engine), by accounting for all operating and power transmission losses in the respective power paths. This analysis was repeated for each technology level due to different component efficiencies and system losses. A detailed power analysis of all systems was conducted to determine:

1. The required type and quantity of APU power for all operating modes and establish the APU design-point (sizing conditions) and define the APU part-load power requirements

2. The required hydraulic, pneumatic, and electrical power throughout the system and define the ratings of these components

TABLE VII. PRIMARY AIRCRAFT MISSION AND POWER REQUIREMENTS

Operating Mode	Ambient Conditions	Power Requirements				Remarks
		Duration	Electrical (kva)	Hydraulic (gpm)	Cooling	
System Checkout	130°F, S.L.	15 min 15 min	14 1	- 8	*	APU operation. Electric and hydraulic power not simultaneous
Engine** Starting	130°F, S.L.	30 sec*** (ea engine)	4	-	*	APU operation. Electrical power simultaneous with engine starting.
Standby	130°F, S.L.	5 min	15	1	*	Main engine operation.
Cruise	95°F, 4000 ft	3 hr	9 avg 40 peak	5 avg 8 peak	*	Main engine operation

*Avionic heat dissipation, 2700 w
Optional additional requirement, 15,000 Btu/hr cockpit cooling

**Main engines: 1500 hp rated each
Starting power approximately 17 to 20 shp at engine starter pad, depending upon type of starting system

***Starting time is maximum at 59°F, S.L. Time at other ambients may vary, depending upon type of starting system.

3. The system size, weight, and performance for subsequent takeoff-gross-weight analysis and to establish the basis for other system comparison parameters

APU power requirements thus determined were based on 130°F, sea level conditions. A second specified operating condition is 95°F at 4000 ft. Since an APU sized for the sea level condition will fulfill the 4000-ft condition and the APU is capable of furnishing the required power at any lower ambient temperature, APU's sized for 130°F sea level operation will be used.

The accessory gearbox components that furnish the primary electrical and hydraulic system checkout power were generally sized by the in-flight power. The exceptions occurred in systems with a hydraulic main engine starting system. This necessitated increasing the utility pump size to approximately 13 to 14 gpm. The 40-kva generator had sufficient capacity to perform a main engine start in those systems where electrical starting was used.

Other components were added as required for a particular system; i.e., a hydraulic motor, electric motor, air turbine motor, or a shaft attachment was added to the accessory gearbox to facilitate driving the gearbox from the APU. A pump, generator, shaft, etc., were added to the APU to produce this power. Because of the wide variations in power transmitted by each system and operating mode, it was necessary to determine a range of component sizes and unit performance. Therefore, component performance was defined in terms of full-load, part-load, and no-load to properly assess the system power. The hydraulic, electrical, and pneumatic component sizing is discussed in Section 6.

Results of System Power Analysis

The APU and main engine power for the secondary power system in each operating mode was required for a computer program that, with component sizes, weights, and other system parameters, was used to select a recommended system (Section 8). The computer printout sheets (Appendix I) show a tabulation of system power requirements for the final candidate systems in terms of shaft power and bleed airflow from the APU or main engine, as required in the various mission modes. Each sheet contains data for one system, which is identified by number, technology level, and whether an ECS is included.

The equivalent shaft horsepower (eshp) shown for an APU is a convenient method of expressing the power rating. It is defined as the sum of the shaft power and the power required to compress the bleed-air; the maximum eshp thus establishes the size of the APU. Table VIII shows maximum eshp values to establish the APU design-point for each candidate system.

Comparison of the eshp values shows that APU in systems without ECS are sized by the engine starting requirement, whereas, in most cases, the APU in systems with ECS are sized by the sum of the system checkout power and the ECS bleed airflow requirement.

In the checkout mode, the electrical power was generally higher than the hydraulic power requirement. However, in some systems having an electrical link from the APU to the accessory gearbox, this was reversed, because the electrical power could be obtained from the APU generator. For a strict equal-basis comparison, all checkout power should be obtained from the accessory gearbox components and would increase the power level of these electrical link systems. However, these systems are generally not competitive with other types, even with the reduced power requirement.

The minimum APU design-point eshp occurs in two of the systems having no power link between the APU and the accessory gearbox (Systems 1.0.0.1 and 1.0.0.2). These systems have a pump and generator mounted on the APU that can supply power for checkout and not accumulate the transmission and component drag losses of the accessory gearbox. However, systems of this type do not provide many of the advantages and the flexibility of those that operate the accessory gearbox. For example, checkout operation cannot be performed on the actual pumps or generator in flight; maintenance requiring operation of the accessory gearbox cannot be performed; and an additional pump and generator are required.

TABLE VIII. DESIGN-POINT ESHP AT APU						
	Technology Level					
	I		II		III	
SPS	W/O ECS	W/ECS	W/O ECS	W/ECS	W/O ECS	W/ECS
1.0.0.1	38.2	70.0	35.5	58.8	33.6	51.1
1.0.0.2	36.0	71.4	34.4	60.2	33.9	52.4
1.0.0.3	58.4	70.3	56.7	58.8	52.9	52.9
1.1.1.0	77.7	95.6	74.9	87.5	63.0	74.0
1.1.2.0	73.0	100.4	70.1	67.8	63.0	76.2
1.1.3.0	114.9	114.9	109.7	109.7	98.8	98.8
1.1.0.1	56.5	99.6	58.0	87.2	47.7	74.0
1.1.0.2	58.4	103.7	58.7	91.1	50.2	77.3
1.1.0.3	59.5	88.9	54.3	78.2	50.9	66.4
1.2.1.0	66.9	118.7	63.4	95.0	56.4	82.9
1.2.2.0	62.5	94.2	59.3	81.3	55.4	69.6
1.2.3.0	99.1	99.1	93.0	93.0	84.6	84.6
1.2.0.1	56.2	92.6	52.7	79.2	47.8	67.8
1.2.0.2	54.7	92.6	52.1	79.2	48.4	67.8
1.2.0.3	66.3	75.5	61.5	63.6	56.8	56.8
1.3.1.0	62.4	98.5	58.5	90.4	51.5	77.7
1.3.2.0	58.5	83.7	54.4	70.0	50.4	57.7
1.3.3.0	86.9	86.9	81.8	81.8	77.2	77.2
1.3.0.1	44.6	89.9	42.7	77.2	37.8	65.5
1.4.1.0	45.3	81.5	44.9	70.3	40.4	59.9
1.4.2.0	43.9	79.1	42.0	67.3	40.2	57.8
1.4.3.0	68.5	77.3	65.9	65.9	61.4	61.4
1.4.0.1	45.0	77.9	42.0	65.9	38.9	56.8
2.4.1.0	45.3	81.5	44.9	70.3	40.4	59.9
2.4.2.0	43.9	79.1	42.0	65.1	40.2	57.8
2.4.3.0	68.5	77.3	65.9	65.9	61.4	61.4
2.4.0.1	45.0	77.9	42.0	64.0	38.9	56.8

6. COMPONENT TRADE-OFFS AND SIZING

This section describes the results of the trade-off studies of all SPS components and subsystems. The SPS components include the electrical, hydraulic, and pneumatic systems, accessory gearbox, and the main engine starting system. The ECS was evaluated as a desired addition to the SPS, and a special combination of the two was also considered.

These SPS components and subsystems were evaluated to determine the appropriate design, performance, weight, volume, and installation parameters necessary to permit the comparison of candidate systems at each technology level. During the analysis, components and subsystems were considered to ensure that reliability, vulnerability, maintainability, complexity, and life-cycle costs were not compromised.

6.1 ELECTRICAL SYSTEM

The primary electrical system consists of two generators mounted on the accessory gearbox, plus associated controlling and power conditioning equipment to produce the required amount and quality of power. Each generator is rated at 40 kva, 400 Hz, and 120/208 v. The system includes a generator control unit, contactor, 200-amp transformer-rectifier, and interconnecting cable as shown on Table IX.

Ten candidate systems have APU-mounted generators ranging in size from 14 to 57 kva (Table X). The 14-kva generators for Systems 1.0.0.1 and 1.0.0.2 are for electrical system checkout, and the 20-kva generators for Systems 1.0.0.3, 1.1.0.3, and 1.2.0.3 are for checkout and main engine starting. The 20-kva continuous-rating size generator is overloaded momentarily during an engine start, but the load is within the intermittent load rating. A detailed breakdown of system component weights and volumes for the 14- and 20-kva generators is included on Table IX.

The remaining systems listed on Table X employ an electric power link from the APU to the accessory gearbox and have no electrical link from the APU to the main engine. The required generator size is given on Table X for these systems, and the generator weight and volume are obtained from Figure 37. The weight and volume of the contactors, T-R units, and cable are proportionately higher than for the 14- and 20-kva generator systems.

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TABLE IX. ELECTRICAL SYSTEM COMPONENTS WEIGHT AND VOLUME

Generator or Motor		Component Item	Technology Level I	II	III
40-kva generators on gearbox	(2)	40-kva generators	68 lb 0.44 ft^3	66 lb 0.42 ft^3	60 lb 0.38 ft^3
	(2)	Generator control units	5.8 lb 0.14 ft^3	5.8 lb 0.14 ft^3	4.0 lb 0.10 ft^3
	(2)	Contactors	6.0 lb 0.07 ft^3	6.0 lb 0.07 ft^3	6.0 lb 0.07 ft^3
	(2)	200-amp T-R units	34.0 lb 0.35 ft^3	34.0 lb 0.35 ft^3	30.6 lb 0.35 ft^3
		Cable	1.0 lb	1.0 lb	1.0 lb
14- or 20-kva generator on APU for electric link to gearbox	(1)	14-kva generator	22.0 lb 0.16 ft^3	21.3 lb 0.16 ft^3	20.0 lb 0.16 ft^3
	(1)	20-kva generator	25.0 lb 0.17 ft^3	24.0 lb 0.17 ft^3	22.5 lb 0.16 ft^3
	(1)	Generator control unit	2.9 lb 0.07 ft^3	2.9 lb 0.07 ft^3	2.0 lb 0.05 ft^3
		Δ Contactor*	0.5 lb	0.5 lb	0.5 lb
		Cable	0.6 lb	0.6 lb	0.6 lb
Main engine starter motors	(2)	Starter motors	52.0 lb 0.11 ft^3	52.0 lb 0.11 ft^3	52.0 lb 0.11 ft^3
	(2)	Starter relays	3.3 lb 0.03 ft^3	3.3 lb 0.03 ft^3	3.3 lb 0.03 ft^3
	(2)	Δ T-R Units*	26.0 lb 0.13 ft^3	26.0 lb 0.13 ft^3	26.0 lb 0.13 ft^3
		Cable	11.0 lb 0.04 ft^3	11.0 lb 0.04 ft^3	11.0 lb 0.04 ft^3

*The delta weights and volumes represent the additional weight and volume for the listed number of units in addition to that for the two 40-kva generators.

TABLE X. APU GENERATOR KVA RATINGS[a]

System	Technology Level		
	I	II	III
1.0.0.1[b]	14	14	14
1.0.0.2[b]	14	14	14
1.0.0.3[c]	20	20	20
1.1.0.3[c]	20	20	20
1.2.0.3[c]	20	20	20
1.3.1.0[c] [d]	37.5	36	32.5
1.3.1.0[f] [e]	57	51	42
1.3.2.0[c]	35	34	32
1.3.3.0[c]	56	53	46
1.3.0.1[f]	26	25	23

(a) These ratings are required for electrical links to the accessory gearbox, the main engine starter motor, or system checkout

(b) Sized by electrical system checkout power requirements

(c) Sized by engine starting requirements

(d) Without an ECS

(e) With an ECS

(f) Sized by hydraulic system checkout requirements

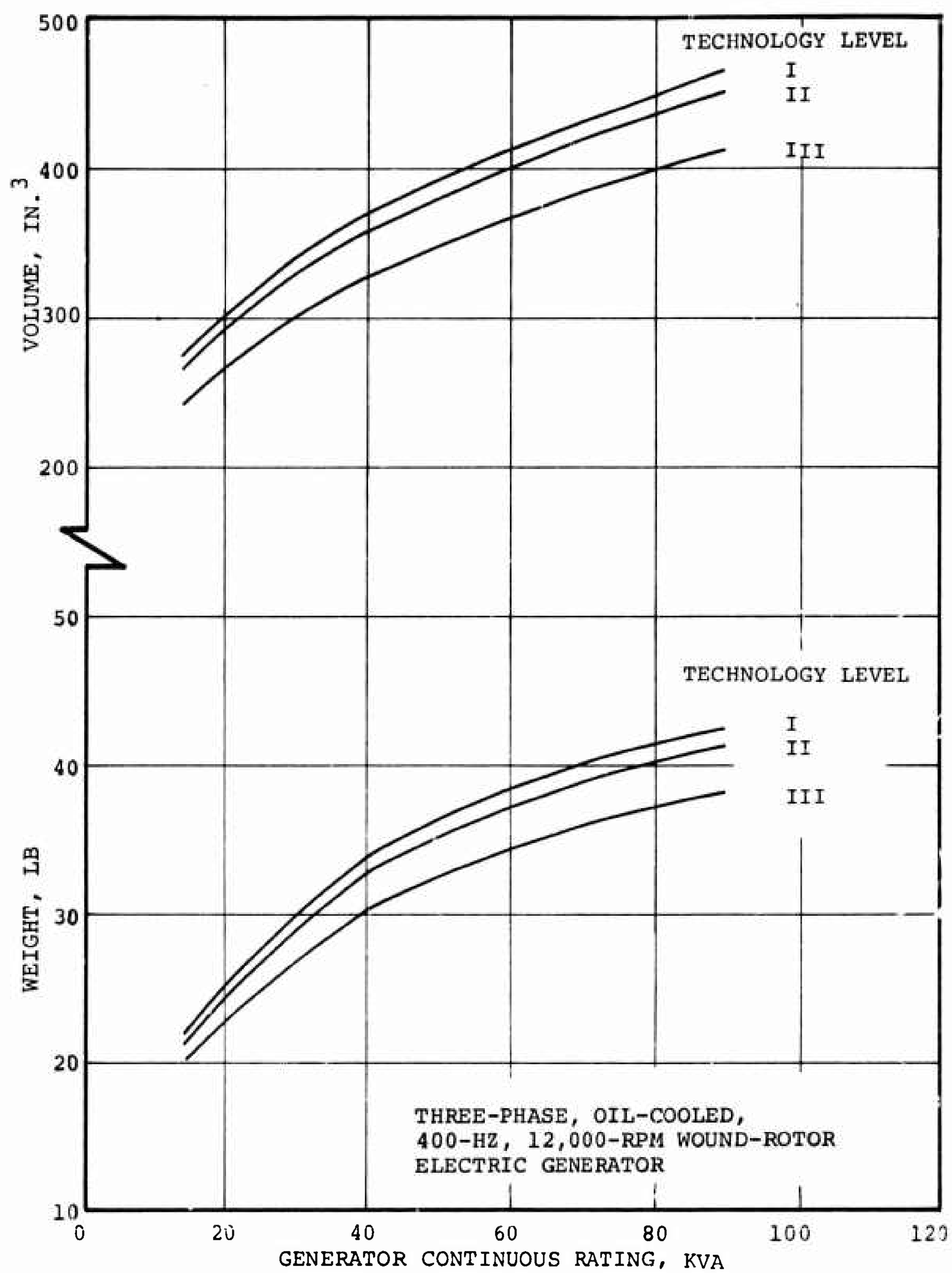


Figure 37. Electric Generator Weight and Volume.

The kva and power levels for the 14- and 20-kva generator systems do not vary with the time period, because the 14 kva is a power requirement for all technology levels. The possible improvements in engine starting motors (considering the 20-kva system) do not significantly affect the overload rating of a 20-kva generator.

The gearbox electric motor power requirements are given on Table XI. The lessening power for the advanced technology levels is a reflection of efficiency improvements in all parts of the power linkage. The weight and volume of these motors are obtained from Figure 38.

Electrical engine starting systems used dc starter motors. DC power was obtained from the ac system by means of a transformer-rectifier (TR). The ac power is furnished either from an APU-mounted generator or from one of the primary system 40-kva generators. A current-limiting feature was added to the TR unit to obtain the desired torque-speed characteristic from the motor. The weight and volume of the starter motors and their system components are included on Table IX. The analysis of electrical starting systems is included in Section 6.5.

Efficiency levels of the gearbox motor and the APU generator were obtained from the schedule shown on Table XII. The horsepower required to drive the 40-kva generator on the gearbox for the several operating modes is given on Table XIII.

TABLE XI. GEARBOX ELECTRIC MOTOR HORSEPOWER

System	Technology Level		
	I	II	III
1.3.1.0[a][b]	39	37	34
1.3.1.0[d][c]	66	59	50
1.3.2.0[a]	36	35	33
1.3.3.0[a]	60	57	50
1.3.0.1[d]	25	24	22

[a] Sized by engine starting requirements
[b] Without an ECS
[c] With an ECS
[d] Sized by hydraulic system checkout requirements

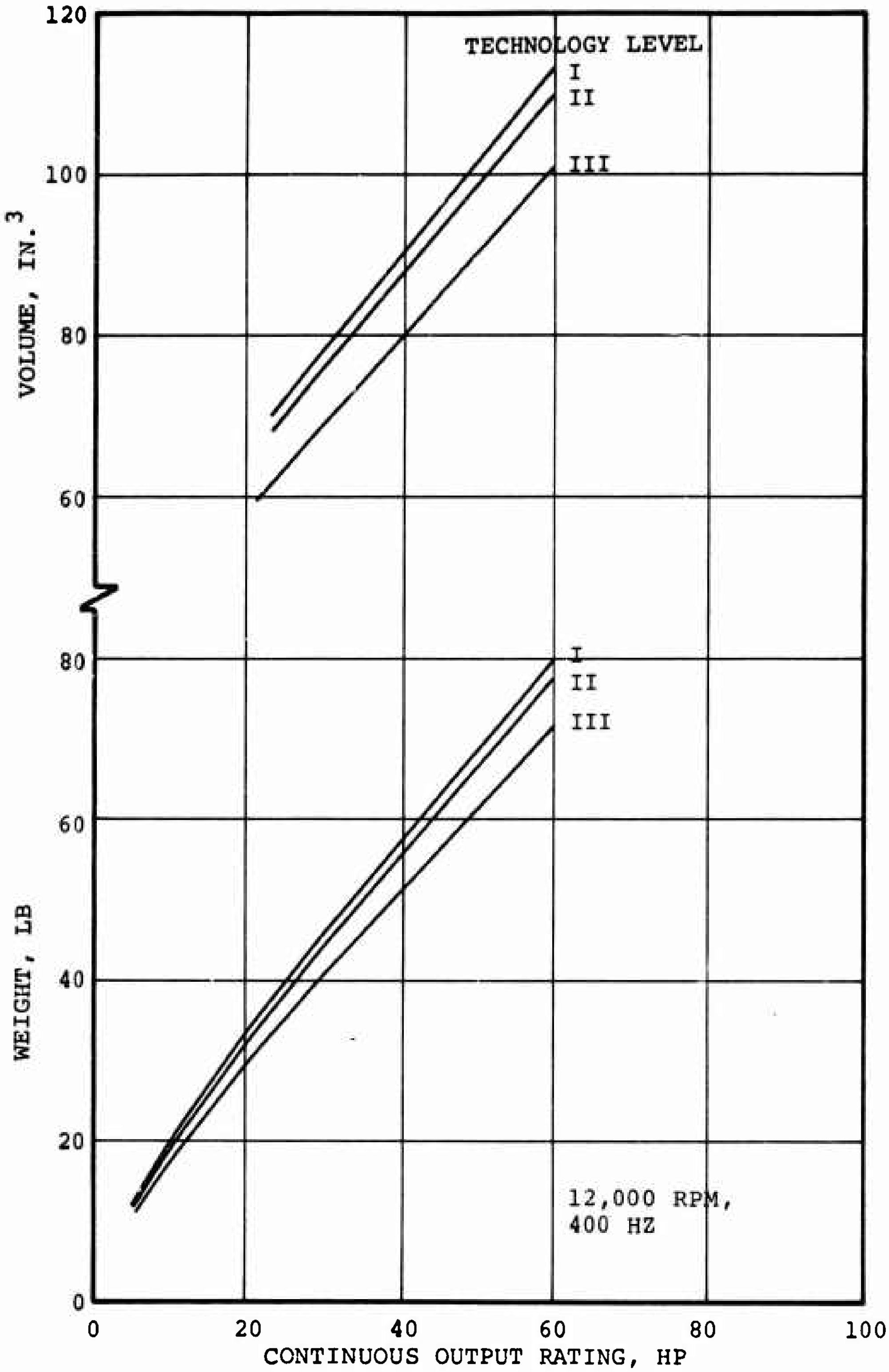


Figure 38. Electric Motor Weight and Volume.

TABLE XII. GEARBOX MOTOR AND APU GENERATOR EFFICIENCY SCHEDULE

Type	Percent Load	Technology Level I	II	III
Generator	100	85	87	89
	50	80	83	84
Motor	100	87	87	88
	50	88	88	89

TABLE XIII. HORSEPOWER REQUIRED BY 40-KVA GENERATOR

Load	Technology Level I	II	III
No-load	2.7	2.7	2.1
4 kva	8.6	8.5	7.9
14 kva	23.3	22.9	21.9
Engine start*	56.7	54.5	51.5

*Includes 4 kva required for airframe and control

6.2 HYDRAULIC SYSTEM

The hydraulic system components in the primary aircraft system were integrated into pump packages mounted on the accessory gearbox. These packages (a 5-gpm pump system for the primary flight control system and an 8-gpm pump system for the utility and redundant flight control system) include the pump, reservoir, filters, valves, switches, line couplings, and electrical connector integrated within a single housing. This packaging concept provides a compact, centrally accessible system that reduces weight and space requirements and provides more convenient maintenance and reduced leakage, due to elimination of interconnecting lines between components. A sketch of a typical integrated hydraulic pump package is shown in Figure 39.

Table XIV lists the pump and motor sizes, and Table XV lists selected hydraulic component weights and volumes of candidate systems. The weight and volume of all pumps and motors were obtained from Figure 40. Six candidate secondary power systems, which require an additional pump and motor, have a hydraulic link between the APU and the accessory gearbox. To accommodate these larger system capacities, the basic utility pump packages were adjusted for increased reservoir, valve, and filter sizes, plus additional fluid. Similar adjustments were made for systems requiring hydraulically starting the main engines, when the pump size was increased due to the engine start requirement. The hydraulic transmission lines, system valves, etc., required to interconnect the pumps and motors were sized and included in the system weight and volume. Sizes of motors and pumps represent system requirements, and are not necessarily standard.

Figures 41 and 42 show the delta-pump package and system component weights and volumes as functions of pump flow rating. These curves were used to adjust the system weight and size when additional hydraulic pumps and/or motors were required. The delta weights and volumes indicated are generally applicable to all technology levels. However, the basic pump package weight and volume do decrease with increasing technology levels, due principally to smaller pump sizes and faster operating speed. These weights and sizes are shown as functions of capacity for the flight control and two basic utility system packages. The larger utility pump is for engine start systems. The pump package concept was retained in all systems for the two pumps mounted on the accessory gearbox. Other pumps and motors were added as separate components, and system weight and volume were adjusted as described above.

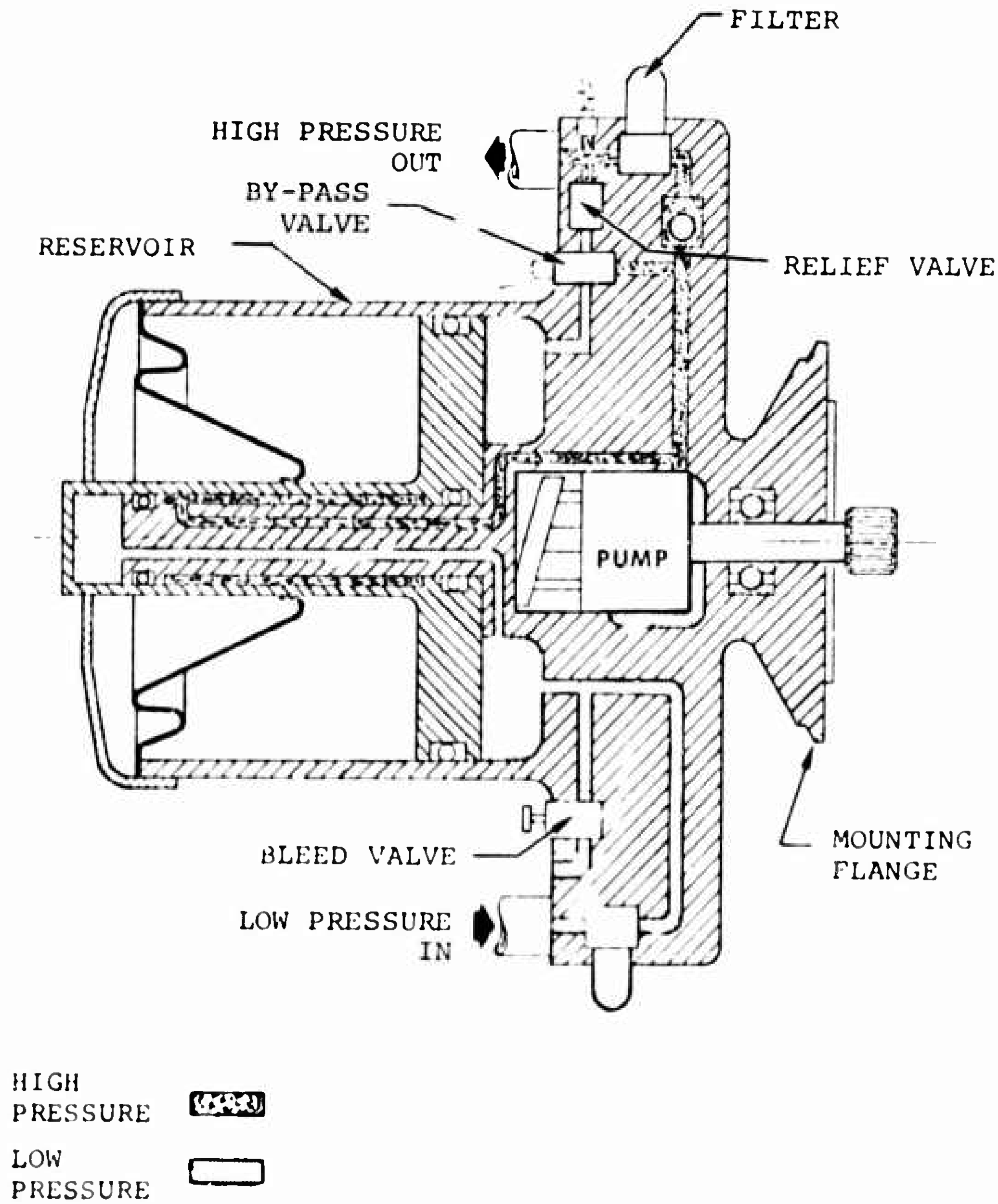


Figure 39. Typical Integrated Hydraulic Pump Package.

TABLE XIV. HYDRAULIC PUMP AND MOTOR SIZES (IN.^{3}/REV)

System	Technology Level I APU Pump	I Gearbox Pump*	I Gearbox Motor	II APU Pump	II Gearbox Pump*	II Gearbox Motor	III APU Pump	III Gearbox Pump*	III Gearbox Motor
1.0.0.1	0.195	0.195	-	0.17	0.17	-	0.13	0.13	-
1.0.0.2	0.37	0.195	-	0.33	0.17	-	0.27	0.13	-
1.0.0.3	0.195	0.195	-	0.17	0.17	-	0.13	0.13	-
1.1.2.0	-	0.37	-	-	0.33	-	-	0.27	-
1.1.0.2	0.37	0.195	-	0.33	0.17	-	0.27	0.13	-
1.2.1.0	1.20	0.195	0.87	0.94	0.17	0.87	0.74	0.13	0.68
1.2.1.0	2.70	0.195	2.35	2.00	0.17	1.50	1.25	0.13	1.18
1.2.2.0	1.29	0.37	1.15	0.87	0.33	0.83	0.72	0.27	0.66
1.2.3.0	2.0	0.195	1.80	1.67	0.17	1.50	1.24	0.13	1.12
1.2.0.1	0.75	0.195	0.70	0.66	0.17	0.61	0.46	0.13	0.44
1.2.0.2	0.91	0.195	0.75	0.80	0.17	0.61	0.58	0.13	0.44
1.2.0.3	0.75	0.195	0.70	0.66	0.17	0.61	0.46	0.13	0.44
1.3.2.0	-	0.37	-	-	0.33	-	-	0.27	-
1.4.2.0	-	0.37	-	-	0.33	-	-	0.27	-
2.4.2.0	-	0.37	-	-	0.33	-	-	0.27	-
All Others	-	0.195	-	-	0.17	-	-	0.13	-
Flight System	-	0.10	-	-	0.09	-	-	0.073	-

*Most pumps are for the utility system, with the exception that the last one is for the flight control system and is common to all systems.

TABLE XV. SELECTED HYDRAULIC SYSTEM COMPONENT WEIGHTS AND VOLUMES

	Technology Level					
	I		II		III	
Characteristics	Wt (lb)	Vol (ft^3)	Wt (lb)	Vol (ft^3)	Wt (lb)	Vol (ft^3)
Basic pump package (accessory gearbox)						
Flight control system, 5 gpm	13.5	0.36	13	0.36	12.5	0.35
Utility system, 8 gpm	16.5	0.48	15.7	0.48	15.2	0.47
APU pump systems (no gearbox link)						
Utility pump, 8 gpm	4.4	0.02	3.6	0.02	2.7	0.02
Lines & valves/Δ utility package	3/.3	0.02	3/.3	0.02	3/.3	0.02
Engine start pump	See engine start systems					
Engine start systems						
Pump (APU)	6.0	0.03	5.4	0.03	3.8	0.03
Pump (accessory gearbox, utility package)	21.8	0.69	21.0	0.69	20.0	0.68
(2) Starter motors	25.6	0.12	25.0	0.12	23.0	0.10
(2) Start valves	2.2	0.01	2.2	0.01	2.2	0.01
Lines						
APU to engine, 14 ft 1/2 in. steel + 3/8 in. aluminum	9.3	0.05	9.3	0.05	9.3	0.05
Gearbox to engine, 10 ft 1/2 in. steel + 3/8 in. aluminum	6.7	0.04	6.7	0.04	6.7	0.04

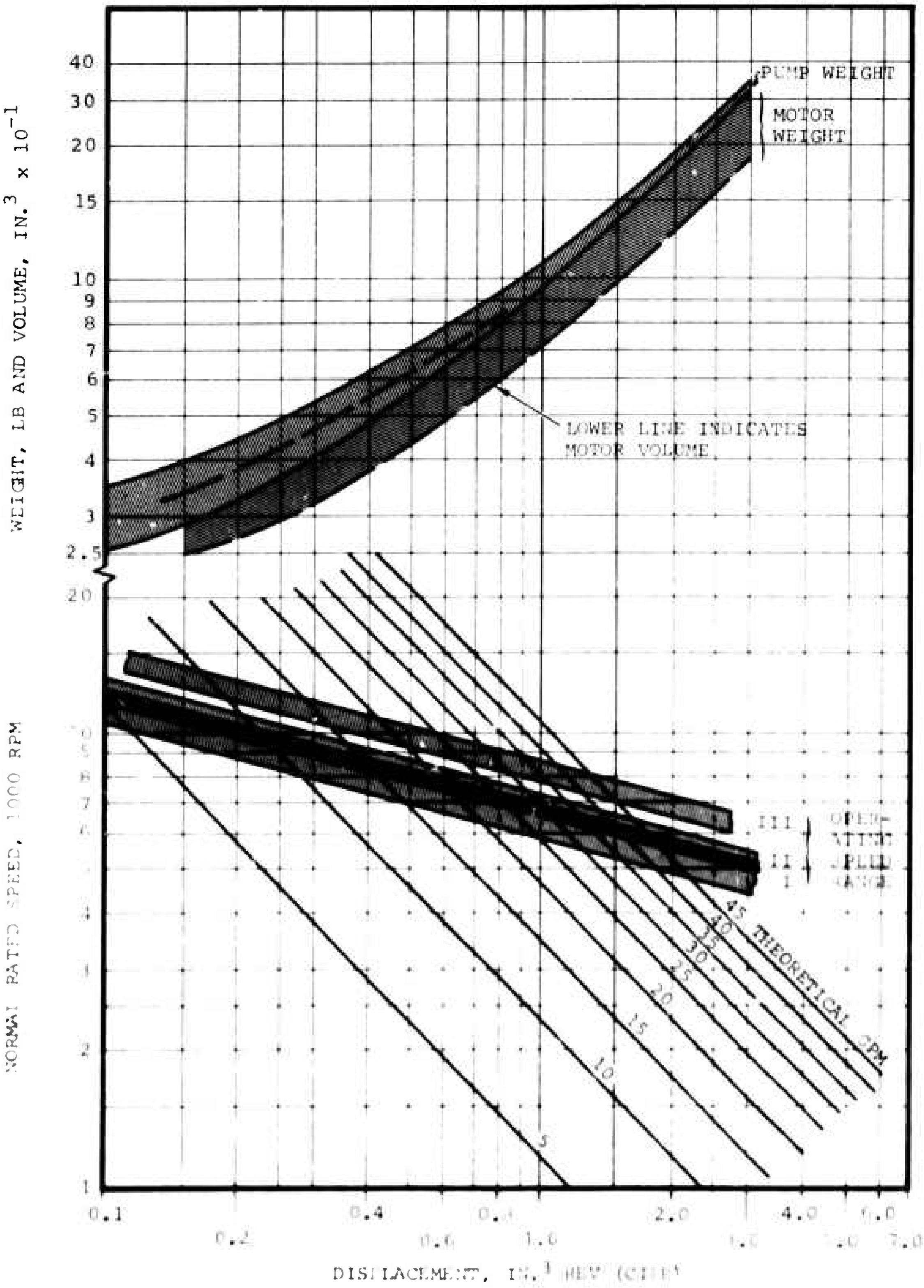


Figure 40. Variable Displacement Hydraulic Pump and Fixed Displacement Motor Sizing.

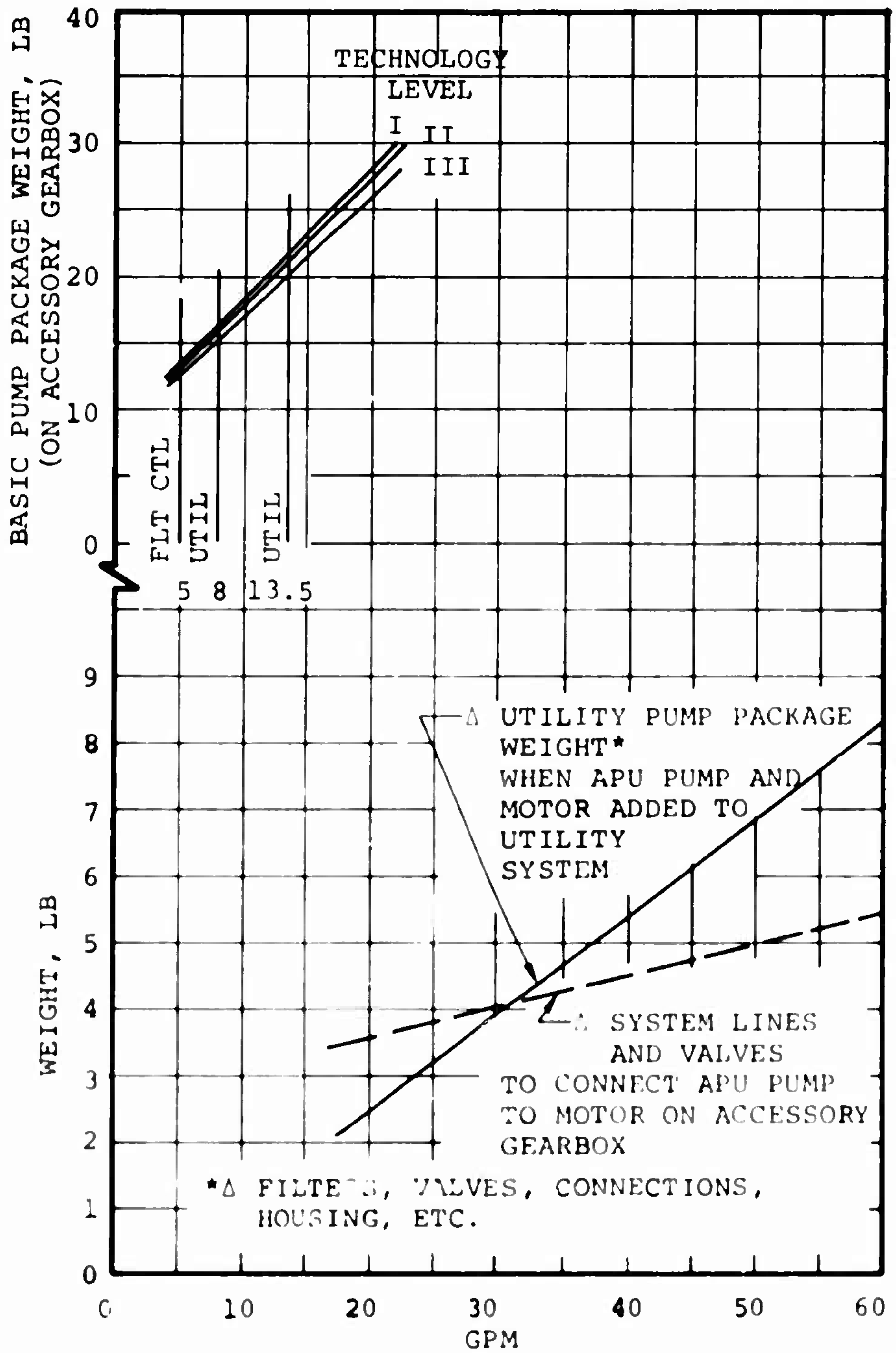


Figure 41. Hydraulic Pump Weights.

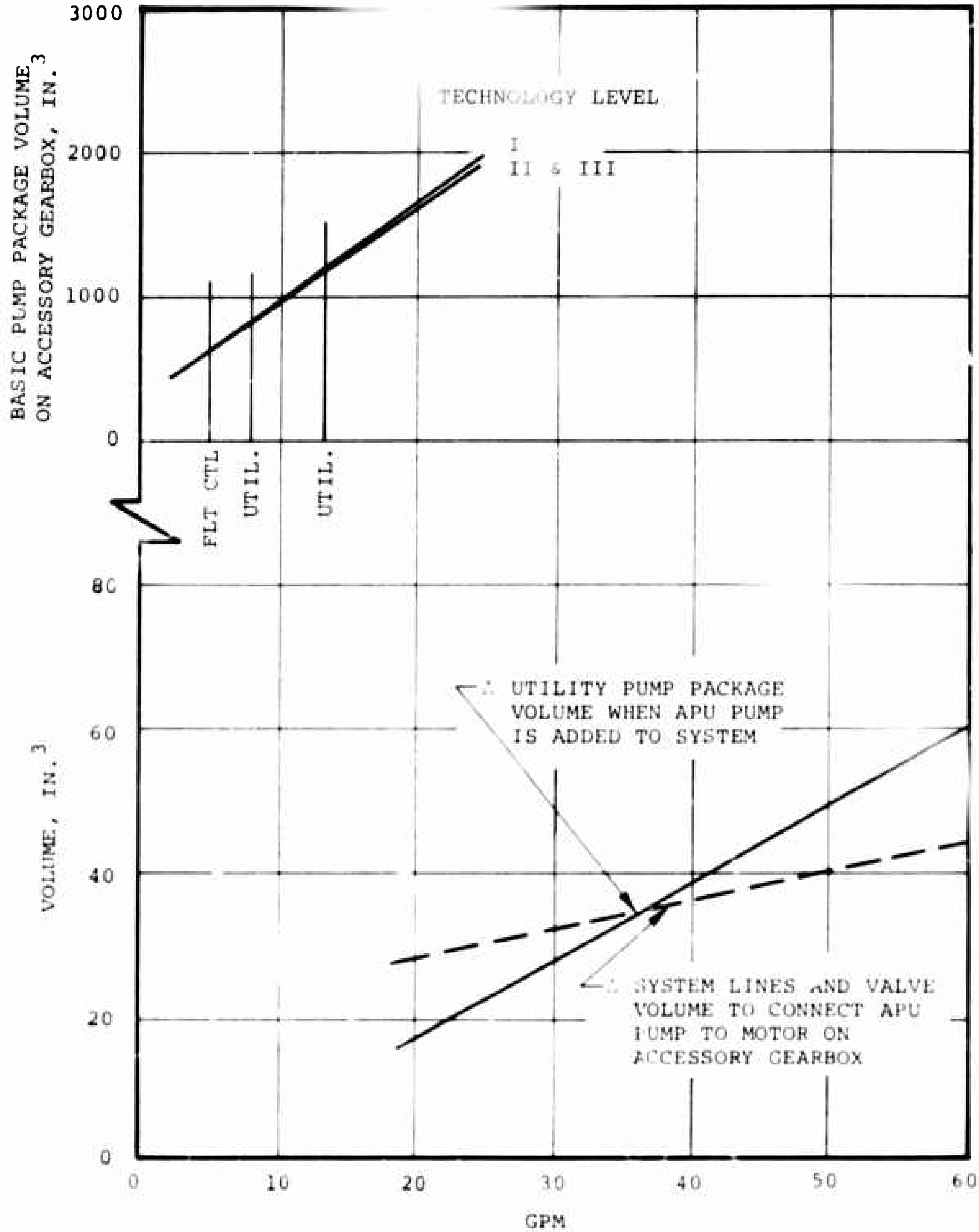


Figure 42. Hydraulic Pump Volumes.

Figure 40 contains generalized sizing curves for variable displacement pumps and fixed displacement motors, used in candidate systems requiring additional pumps and motors. The curves were constructed from composite data obtained from the survey of manufacturers and from supplemental data. The pump- or motor-rated speed and displacement are indicated in Figure 40 at the juncture of the theoretical component flow and the speed line band for a particular technology level. The component weight and volume are found in Figure 40 as functions of displacement. The actual flow was obtained by applying a volumetric efficiency of 97 percent to the theoretical flow.

Fixed-displacement motors were required on most accessory gearboxes in the hydraulic link systems; System 1.2.0.2 required a variable displacement type. The motor weight is, therefore, heavier than that derived from the curve for fixed-displacement motors. All engine starters were variable displacement types, and a gearbox and overrunning clutch were included in the weight and volume analysis.

The pump efficiencies for Technology Levels I, II, and III are 85, 86, and 88 percent, respectively, at full load. The pump horsepowers for the 5- and 8-gpm gearbox pumps and the engine starting pump are given on Table XVI.

TABLE XVI. HORSEPOWER REQUIREMENTS FOR SELECTED HYDRAULIC PUMPS

		Technology Level		
Pump	Load	I	II	III
5 gpm	Full	10.3	10.2	9.9
	No-load	1.6	1.4	1.2
8 gpm	Full	16.5	16.3	15.9
	No-load	2.5	2.3	1.9
Engine start	Full	27.6	26.2	25.9
	No-load	4.1	3.7	3.1

6.3 PNEUMATIC SYSTEMS

Pneumatic components were required in 14 of the 27 basic candidate systems and in all systems when an air-cycle ECS was included. Depending upon the specific systems, these components may include an integral bleed APU, air turbine starters for main engine starting, an air turbine motor for pneumatically linking the APU to the accessory gearbox, an air compressor mounted on the gearbox (which may be driven by the APU or the main engines and may supply air for engine starting and/or for the air-cycle ECS), and the ECS package.

6.3.1 Air Turbine Starters

The air turbine starter is composed of six major components: an inlet plenum, a turbine assembly, a reduction gear system, an overrunning clutch, a speed switch, and an output shaft. The turbine section includes a single-stage turbine wheel with a full admission nozzle and a containment ring. The overrunning clutch engages and drives the starter output shaft during the starting cycle and disengages centrifugally for overrunning at engine operating speeds. The starter is designed to accomplish the starting cycle automatically, when used in conjunction with an air shutoff valve closed by a signal from the centrifugally operated speed switch. The starter is also designed to function with bleed-air from a main engine and provide cross-bleed start capability in the aircraft. The pneumatic starting system performance is discussed in Section 6.6.

The air turbine starter and valve description are shown on Table XVII for the three technology levels. Since the main engine requirements were constant for all technology levels, the decreases in size and weight are the result of increased speed and turbine efficiency, higher system pressure, advanced materials, and improved transmission (gearbox) efficiencies. The turbine efficiency for Technology Level I is slightly lower than air turbine starters currently used on production aircraft. Well-designed starters are exhibiting overall efficiencies (turbine plus gearbox) of approximately 77 percent. However, because of the small starting power required of the advanced technology engines in this study (approximately 18 shp at 59°F, sea level), the starter turbine size will be in the small, higher speed region in order to maintain a full admission nozzle with a turbine diameter of 2 in. or less. Thus, the overall efficiency indicated in Table XVII is the estimated turbine and mechanical efficiency achievable in this small size component.

TABLE XVII. AIR TURBINE STARTER DESCRIPTION			
	Technology Level		
Components	I	II	III
ATS			
Efficiency (overall) pct	73	76	78
Weight, lb	7	6	4.5
Volume, $in.^3$	88	71.5	53
Major diameter, in.	4	3.75	3.5
Length, in.	7	6.5	5.5
VALVE (Pressure Regulator)			
Line size, in.	1.5	1.25	1.0
Weight, lb	3.5	3.0	2.5
Volume, $in.^3$	40	36	30
Pressure drop, pct of inlet pressure (wide-open valve)	0.85	0.80	0.60

6.3.2 Air Turbine Motors

The air turbine motors are constant output speed units that convert pneumatic power into mechanical power by means of a turbine wheel and speed-reduction gear system. These units accelerate to governed speed upon opening the shutoff valve at the turbine inlet, and function automatically at a governed speed by adjustment of the airflow according to load requirement. Because of the necessary load range, variable turbine nozzles were included that operate in conjunction with a speed sensor to hold the governed speed over the load and inlet pressure ranges. This control method is preferred over that of throttling the inlet airflow, since off-design efficiencies will be higher.

The ATM units varied in size from 22 to 67 hp, depending upon the system and technology level for this power class. For the system pressure levels, the use of turbomachinery is preferred over the positive displacement air motors because of the inherent lower weight, higher efficiency, and compatibility with the available bleed-air pressure levels.

Table XVIII shows the ATM's as sized for each system and technology level. Weights include the inlet valve, turbine wheel containment, variable turbine nozzles, constant speed controls, and gearbox. The pneumatic ducting is included for all systems for a distance of 4 ft between the APU and ATM in Table XIX. The decrease in ducting size with technology level is from decreased airflow as a result of increased system pressure and increased ATM efficiency. Efficiency levels for Technology Levels I, II, and III are 75, 76, and 78 percent, respectively. ATM weight and size trends are shown in Figure 43.

6.3.3 Air Compressors

Shaft-driven air compressors are required in candidate systems to furnish pneumatic power when the APU is designed as a shaft power machine. In some systems, pneumatic power is required for engine starting and/or the ECS. By mounting on the accessory gearbox, the compressor may be driven by the APU for ground operation or by the main engine in flight. The latter would eliminate bleeding the main engines.

Single-stage centrifugal air compressors are used in this study. The compressor pressure requirements are the same as those for the APU bleed-air shown on Table XX, which includes a description of the compressors used in the study. The weight and volume trends are given in Figure 44. The compressor unit is designed to mount on the accessory gearbox and

TABLE XVIII. AIR TURBINE MOTOR DESCRIPTION

System	Technology Level I			Technology Level II			Technology Level III		
	Power Rating (hp)	Weight (lb)	Volume (ft^3)	Power Rating (hp)	Weight (lb)	Volume (ft^3)	Power Rating (hp)	Weight (lb)	Volume (ft^3)
1.1.1.0	45	28.5	0.12	43.5	25	0.10	39	19.5	0.06
1.1.2.0	42.5	28.1	0.12	41	24.5	0.10	39	19.5	0.06
1.1.3.0	67	33.5	0.18	64	30.3	0.16	59.5	25.5	0.10
1.1.0.1	32	27	0.10	31	22	0.08	28	16.3	0.05
1.1.0.2	32	27	0.10	31	22	0.08	28	16.3	0.05
1.1.0.3	25	25	0.09	24.5	21	0.08	22	15	0.05

TABLE XIX. DUCTING* DESCRIPTION FOR AIR TURBINE MOTORS

System	Technology Level I			Technology Level II			Technology Level III		
	Diameter (in.)	Weight (lb)	Volume (ft^3)	Diameter (in.)	Weight (lb)	Volume (ft^3)	Diameter (in.)	Weight (lb)	Volume (ft^3)
1.1.1.0	2.0	2.9	0.09	2.0	2.9	0.09	1.5	2.2	0.05
1.1.2.0	2.0	2.9	0.09	2.0	2.9	0.09	1.5	2.2	0.05
1.1.3.0	2.5	5.2	0.14	2.5	5.2	0.14	1.5	2.2	0.05
1.1.0.1	2.0	2.9	0.09	2.0	2.9	0.09	1.0	2.0	0.02
1.1.0.2	2.0	2.0	0.09	2.0	2.9	0.09	1.0	2.0	0.02
1.1.0.3	2.0	2.9	0.09	2.0	2.9	0.09	1.0	2.0	0.02

*Ducting is assumed to be 4 ft long.

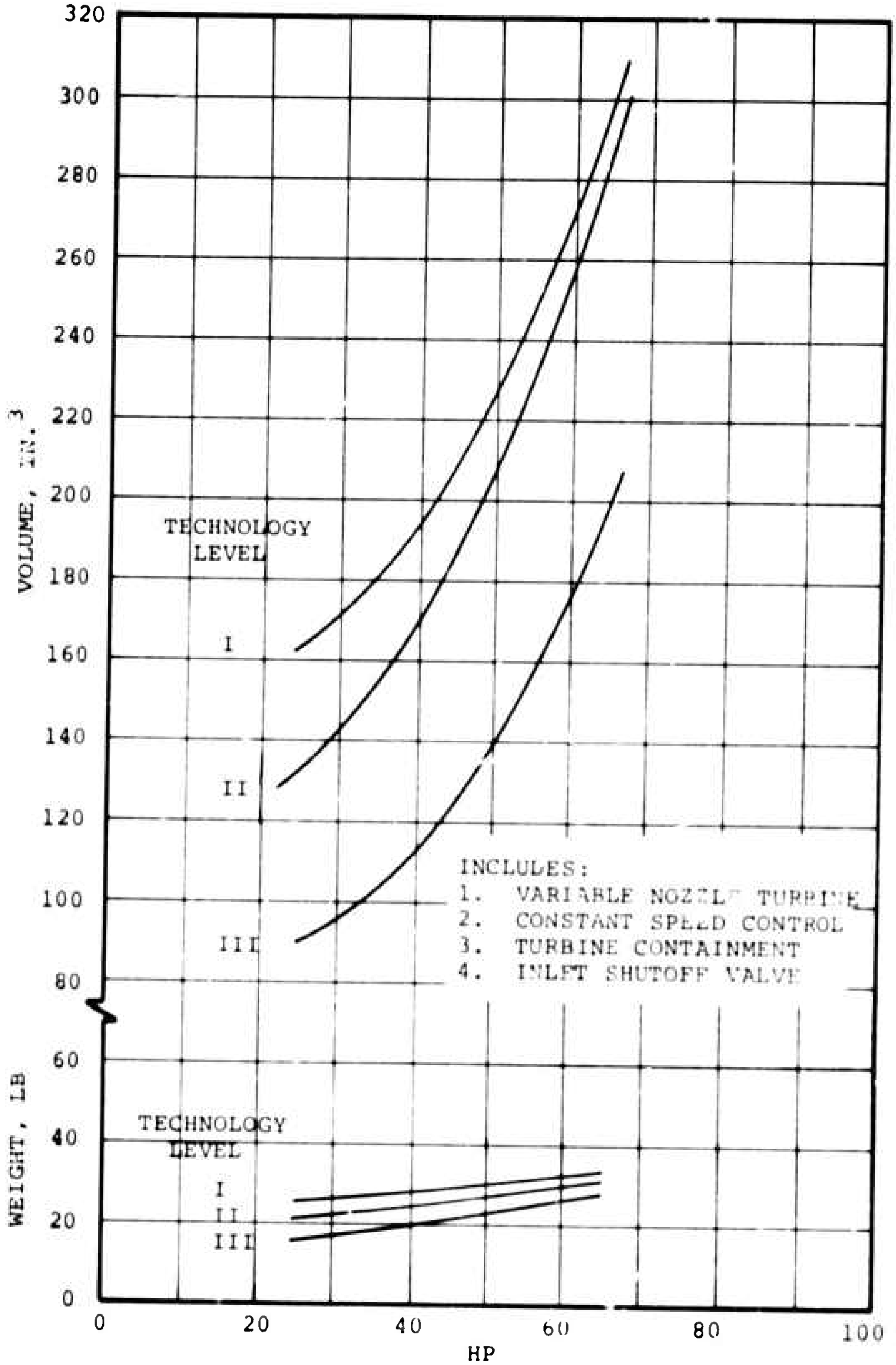


Figure 43. ATM Weight and Volume.

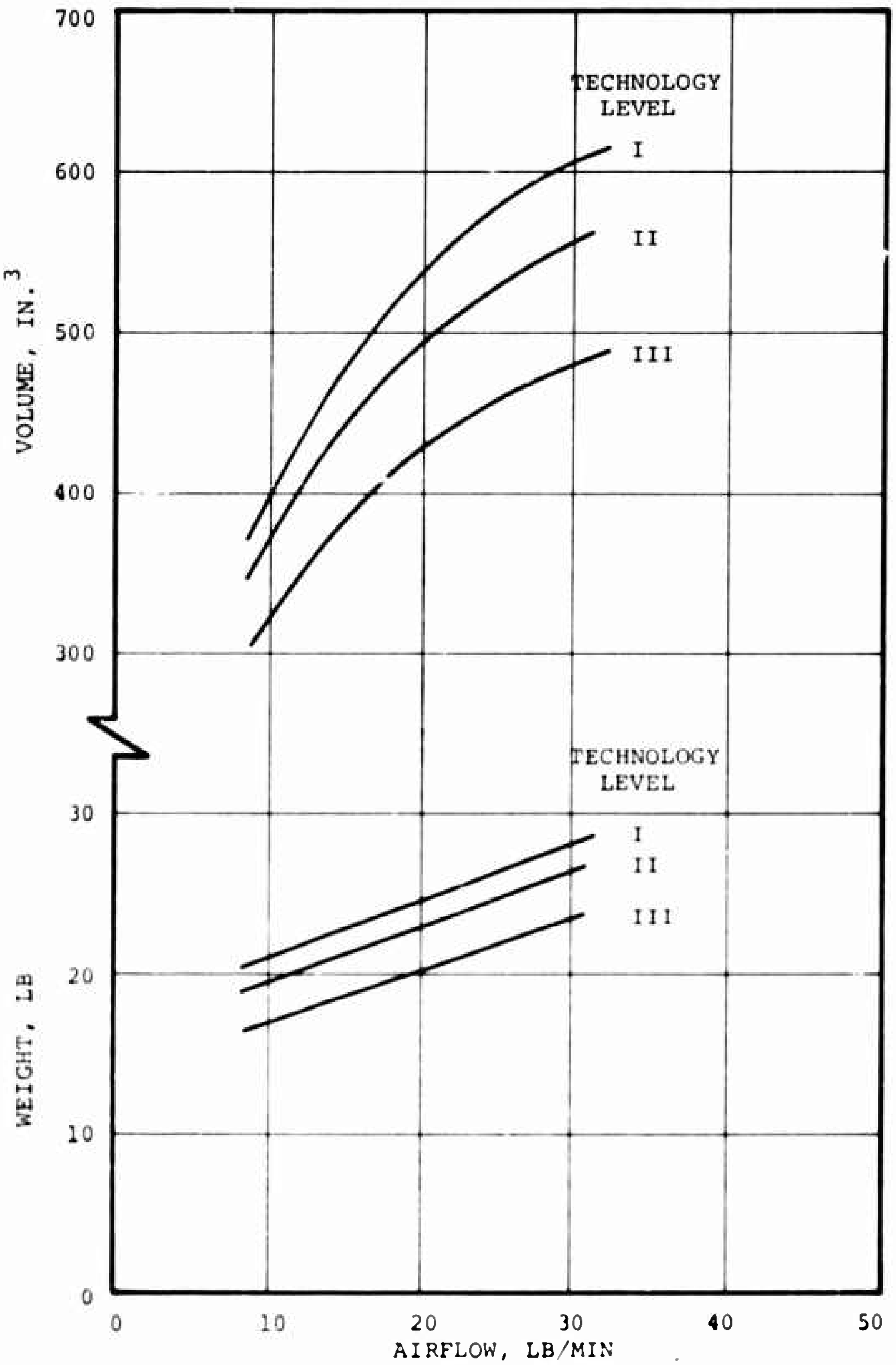


Figure 44. Air Compressor Weight and Volume.

TABLE XX. GEARBOX-MOUNTED AIR COMPRESSOR DESCRIPTION				
System Type	Item	Technology Level I	II	III
All	Pressure ratio	3.5	4.5	5.5
Without ECS	Flow, lb/min	14.1	10.6	8.9
	Weight, lb	22.4	19.6	16.5
	Volume, ft^3	0.27	0.22	0.18
With ECS	Flow, lb/min	23.0	14.3	9.6
	Weight, lb	25.5	20.8	16.7
	Volume, ft^3	0.33	0.25	0.18

operate at essentially constant speed when driven by the APU or the main engine. All compressors include a gearing system to step up the input speed from the gearbox, a clutch to disconnect the unit when compressed air is not required, a lube system, and complete controls to accommodate changes in system airflow requirements. The latter includes a surge valve for regulating flow to within the impeller operating range. The clutch is a fill-and-drain type fluid coupling integral with the compressor gearbox assembly and utilizes the gearbox lubricant as the working fluid.

6.4 ACCESSORY GEARBOX

The accessory gearbox is part of the basic secondary power system and is included in all candidate systems. This gearbox is for mounting and driving the primary system hydraulic pumps and electric generators. For the study, the accessory gearbox was treated as a separate component with a specific weight and volume, according to the requirements of the different systems. The basic gearbox description and the additional pads or drives required for system variations (such as when the gearbox is linked to the APU electrically, hydraulically, pneumatically, or mechanically) or for the addition of an air compressor are shown on Table XXI.

TABLE XXI. ACCESSORY GEARBOX WEIGHTS AND VOLUMES

Components	Technology Level I Wt (lb)	I Vol (ft^3)	II Wt (lb)	II Vol (ft^3)	III Wt (lb	III Vol (ft^3)
Basic gearbox	43	1.3	37	1.3	32	1.2
Added Components*						
Motor Drive Pads:						
Air Turbine	6	0.1	5.3	0.1	4.7	0.1
Hydraulic	6	0.1	5.3	0.1	4.7	0.1
Electric	8	0.1	7	0.1	6.2	0.1
Compressor Drive Pad	6	0.1	5.3	0.1	4.7	0.1
Shaft connection for remote APU	4	-	3.5	-	3 1	-
APU Mount Pad	8	0.1	7	0.1	6.2	0.1

*Additional weight and volume to basic gearbox required.

The basic gearbox is shown in Figure 45. In an actual installation, the gearbox could be attached to the main rotor transmission and share a common oil sump. For this reason, all components have been located on one side. The tail rotor drive is a straight-through shaft from the rotor gearbox and drives the accessory gearbox through a splined gear. For systems having a power link from the APU to the gearbox, an overrunning clutch is required at the tail rotor drive shaft input to allow the gearbox to be independently driven by APU power during systems checkout and maintenance.

The basic gearbox comprises a spur gear train within a magnesium housing. The generators are driven at 12,000 rpm; the hydraulic pump speeds are between approximately 9000 to 16,000 rpm, depending on the technology level.

The gearbox requires a separate internal lubrication pump from the main rotor transmission, to facilitate operation when the main engines are not driving the rotor transmission. This pump is sized to produce all lubrication within the box plus cooling oil for the electric generators. Other components associated with a particular system, such as an electric motor, air turbine motor, or an air compressor, are also furnished cooling oil. Hydraulic elements are cooled separately within the hydraulic system.

The reduced weights for advanced technology levels (Table XXI) are predictions based on the following:

1. Gear weight reductions through the use of higher strength materials, fabricated gear construction, improved gear load-carrying capacity by improved lubrication and cooling methods, and higher speed accessories.

2. Bearing weight reductions by the use of advanced journal bearings throughout the gearbox.

3. Case material advances.

6.5 PRIMARY MAIN ENGINE STARTING SYSTEM

A summation of APU power required for engines starting at 59°F sea level is presented in Table VIII, Page 53, for each candidate system and technology level. APU power is shown in terms of equivalent shaft horsepower (eshp), where the total requirement is a combination of shaft power and the power required to generate the bleed-air. The latter is directly comparable to the power for a separate compressor driven by the

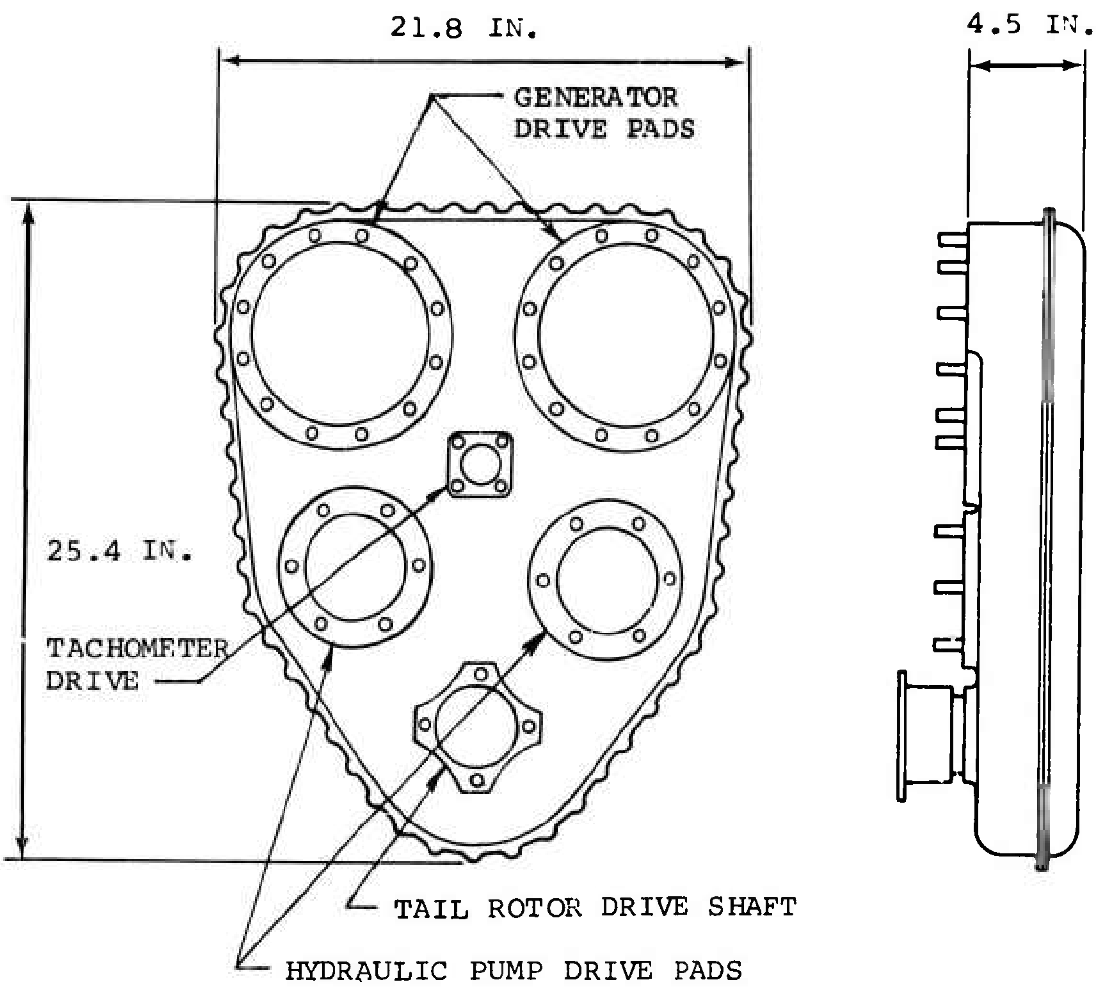


Figure 45. Basic Accessory Gearbox.

APU when it is furnishing compressed air at the same pressure ratio and flow rate. Equivalent shaft horsepower is the shp when no bleed-air is extracted.

The simultaneous 4-kva electrical power, necessary for starting, is produced from the primary electrical system generators on the accessory gearbox by means of the APU-to-gearbox power link. For electrical-link systems, this power is obtained directly from the generator mounted on the APU and does not require operating the accessory gearbox. In determining the total APU power for an engine start, all system and power transmission losses in both the starter and the electrical power link systems were included. For example, in addition to extracting the electrical load from a 40-kva generator, the accessory gearbox load also includes the drag of the unloaded second 40-kva generator, the hydraulic pumps, gearing, and lubrication system losses. Power link losses, such as between the APU and gearbox, were included. These system losses varied, depending upon the candidate SPS, but account for the rather high APU power for engine starting in some systems.

A 30-sec start time from initiation to engine-idle speed at 59°F, sea level, static ambient conditions for the advanced technology engine (ATE) was the criterion for the engine starting analyses. Starting analyses were conducted using pneumatic, hydraulic, and electrical starter motors. The starting times from initiation to engine-idle speed obtained from the analyses are shown on Table XXII. At -65°F, longer

TABLE XXII. START-TIME SUMMARY, ADVANCE TECHNOLOGY ENGINE, SEA LEVEL, STATIC

Starter Motor Type	Ambient Temperature °F	Time to Idle sec
Pneumatic	130	39*
	59	30*
	-65	27*
Hydraulic	59	30
	-65	42
Electric	59	26
	-65	47

*1 sec included for valve opening

starting times for the hydraulic and electric motor were required than for the pneumatic motor, and to stay within an arbitrary start-time limit of 50 sec on a -65°F day, the electrical system 59°F rating was increased (thus decreasing the 59°F day starting time). The reason for this is evident from the torque curves (Figure 46). These curves of the electrical and hydraulic starting systems are essentially constant with ambient conditions. The pneumatic system has more torque at lower temperatures, thus approximating the drag torque increase of the engine with decreasing temperature. Also, the pneumatic starting system produced acceptable starts at 10,000 ft, when sized for sea-level conditions.

If the torque curves of the hydraulic or electrical system of Figure 46 are to be met at extreme hot conditions, the APU rating at 59°F sea level must be increased approximately 30 percent.

For a hydraulic system, it may be feasible to allow the system pressure to decrease and, thus, match the decreased APU power available at the higher ambient temperatures or at altitude. It may also be feasible to use a dual pressure feature in hydraulic systems. This allows a reduction in system pressure and, hence, reduced power for certain operating conditions, such as hot-day ground conditions or at altitude where less starting power is required. This latter feature could be accomplished by an electrically operated, two-position compensator on the pump operated by either an altitude pressure switch or a manual switch.

The electric start curve (Figure 47) shows a constant output torque characteristic in the lower speeds rather than a decreasing torque characteristic with increasing speed. This constant torque output would be accomplished by automatically limiting the motor current. This output characteristic was used to avoid excessively fast starts at higher ambient temperatures while an acceptable low-temperature start was maintained.

For systems with a direct drive from the APU to the accessory gearbox, a fill-and-drain-type fluid coupling is included in the gearbox, to transmit the shaft power and prevent shaft power from being transmitted in either direction when not desired. For systems having a compressor on the gearbox, a clutch is included to uncouple the compressor when operation is not required.

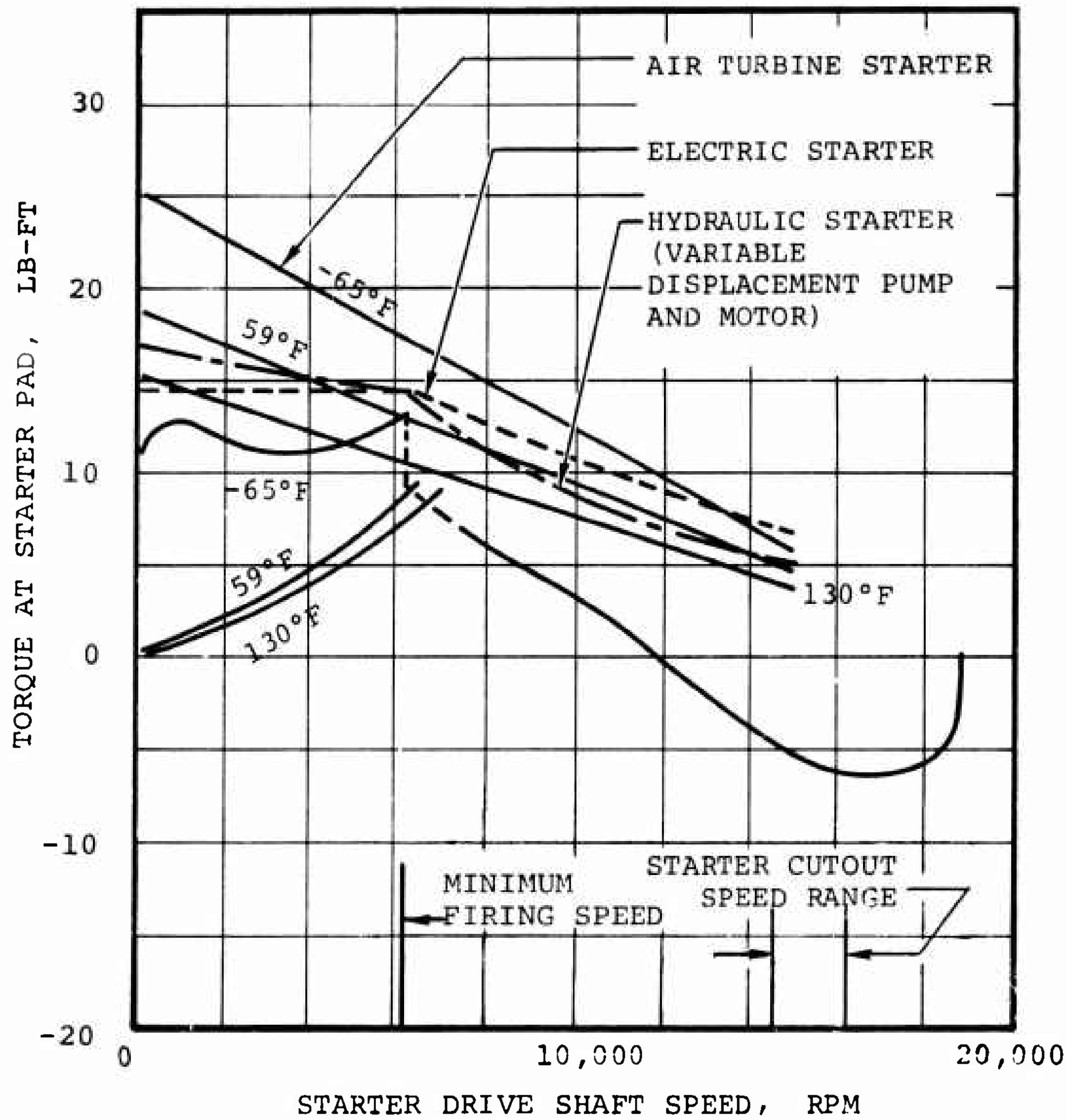


Figure 46. Estimated Starting Characteristics, Advance Technology Engine - Sea Level Static.

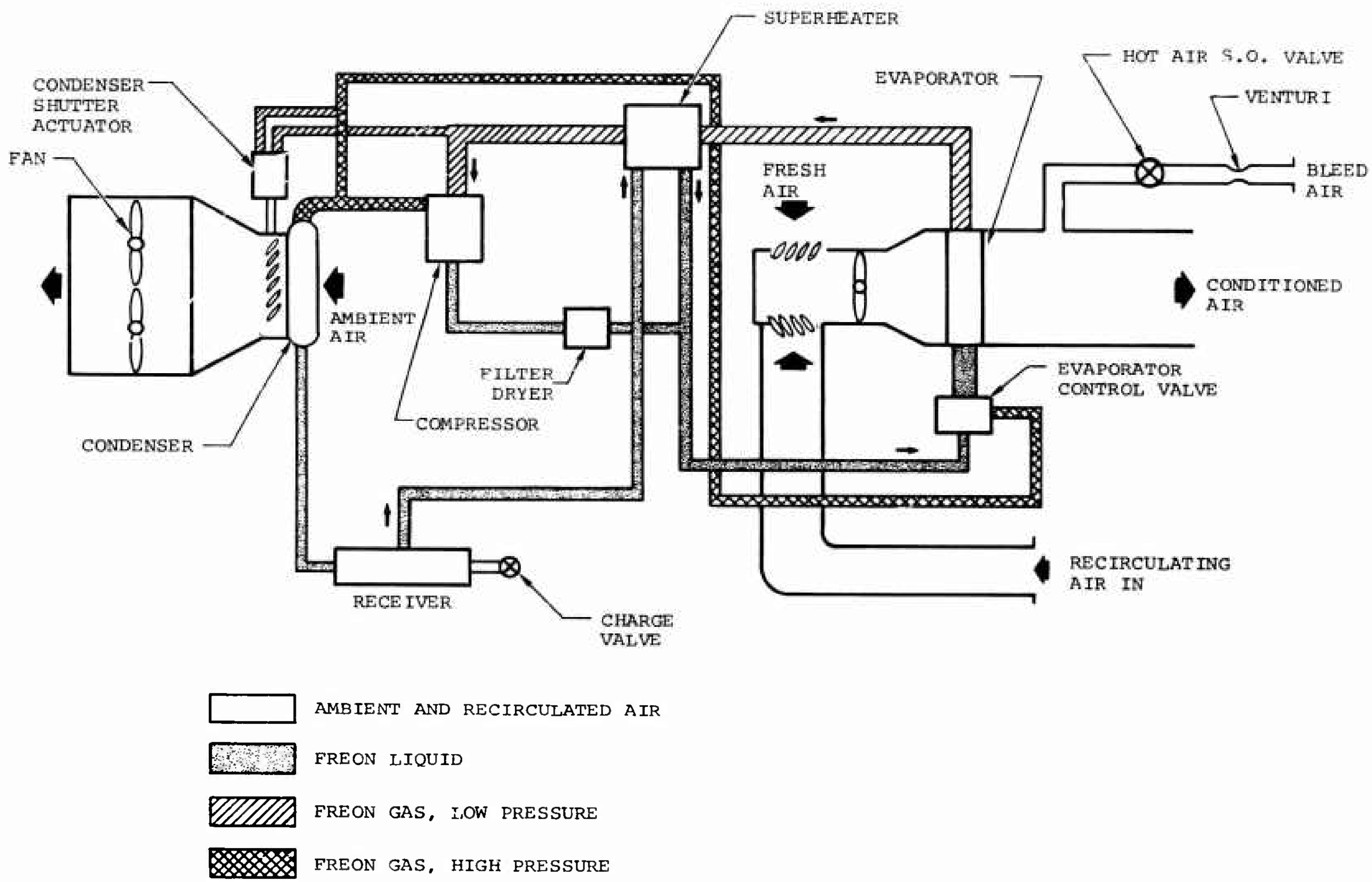


Figure 47. Vapor Cycle ECS Schematic.

Since redundant main engine starting systems were considered as possible additions to the SPS, this analysis was conducted after the selection of the recommended SPS, as discussed in Section 9.

6.6 ENVIRONMENTAL CONTROL SYSTEM

6.6.1 Requirements and Ground Rules

The general requirements of the ECS are (1) ground and flight cooling, heating, and ventilation for the crew compartment; (2) troop compartment heating and ventilation in flight; and (3) avionic cooling.

Ambient extreme conditions considered in the analysis are from -65° to 125°F at sea level, 95°F at 4000-ft altitude for ground operation, and -12°F at 20,000 ft for in-flight operation.

The ECS size was based on the most stringent of two extreme ambient conditions, both of which exceed the requirement of 99- percent frequency of coincident wet and dry bulb temperatures, as defined by the USAF Climatic Center. These extremes are 125°F dry bulb, 28 gr/lb of dry air and 99°F dry bulb and 185 gr/lb of dry air at sea level. Crew compartment cooling load was calculated as 15,000 Btu/hr at a maximum compartment temperature of 80°F. Avionic cooling load was set at 2700 w, with a maximum operating temperature limit of 160°F.

The design cabin heating requirement was 72,600 Btu/hr on a -25°F day, resulting in a compartment temperature of 40°F. Cabin heating calculations were based on a compartment surface area of 265 sq ft and an overall heat transmission coefficient of 0.42, which includes the rotor downwash effect during ground and hover operation.

Compressed air for operation of the air-cycle cooling systems is provided by the APU, shaft-driven compressor, or the main propulsion engine. Airflow rates, pressures, and temperatures used in the analysis for the various technological levels of development are shown on Table XXIII.

Ventilation of troop compartment in flight is assumed to be supplied through an external scoop and on the ground by a ventilating fan. Either system is assumed to provide a velocity of 300 ft/min in the cabin space.

Avionics cooling of the 2700-w cooling load is accomplished by drawing compartment air into the electronic bay by an electrically driven axial-flow fan.

TABLE XXIII. COMPPESSED AIR SOURCE CONDITIONS

Ambient Condition Sea Level		Technology Level								
		I			II			III		
Temperature (°F)	Moisture to Dry Air (gr/lb)	Pressure (psia)	Temperature (°F)	Flow (lb/min)	Pressure (psia)	Temperature (°F)	Flow (lb/min)	Pressure (psia)	Temperature (°F)	Flow (lb/min)
125	28	52	470	23	68	540	15.4	82	605	9.8
95	185	55	440	25	75	525	14.4	90	580	10.9
-25	-	67	330	31.5	86	415	19.1	104	465	12.7
-65	-	71	295	33	87	365	19.7	106	410	13.4
*125	-	51.5	472	10-30	66.1	570	10-20	81	652	10-15
* 95	-	51.5	423	10-30	66.1	515	10-20	81	594	10-15
*-25	-	51.5	233	10-30	66.1	305	10-20	81	365	10-15
*-65	-	51.5	169	10-30	66.1	227	10-20	81	286	10-15

*Shaft driven load compressor performance

6.6.2 Vapor Cycle Systems

In the vapor cycle systems, crew compartment air would be recirculated across the evaporator for cooling. The heat load of the condenser rejects to ambient air circulated by a small fan on the ground and by ram air during flight.

All of the vapor cycle studies were based on the concept of a self-contained package consisting of evaporator; condenser; condenser fan; recirculating fan; an electric-powered, hermetically sealed, centrifugal compressor, and the necessary controls. Condenser temperature was assumed to be 125°F. The compartment is heated by the introduction of engine bleed-air downstream from the evaporator, where cabin air is mixed with the bleed-air in an ejector to reduce temperature gradients before introduction into the new compartment (Figure 47).

The weight and volume of a vapor cycle system for the three technology levels were estimated from design exercises for 1- and 3-ton units, plus an existing 10-ton unit. The weight, volume, and electrical power required by these systems are shown in Figure 48.

Since one-half of the system weight and volume is attributable to heat exchangers and piping, much of the weight reduction anticipated for the advanced technology systems is achieved by higher refrigerant pressures. These higher pressures result in a lower operating efficiency, and the system requires more power. Some weight and volume savings may be obtained from heat exchanger development, such as use of new alloys, better brazing techniques, and improved mechanical joining methods. Advanced technology applied to the compressor wheel design, for higher efficiencies and improved compressor cooling, will tend to lower the weight, volume, and power requirements for the advanced technology periods up to 15 percent.

Since the available bleed-air pressure ratio is 3.5 or higher, air turbine-driven compressors may give further weight and volume savings of 10 or 15 percent. A direct shaft drive would probably not be beneficial, since the weight savings would be largely offset by a clutch mechanism. Either of these configurations requires a shaft seal for the compressor, which is a potential leak source and tends to increase maintenance manhours per flight hour.

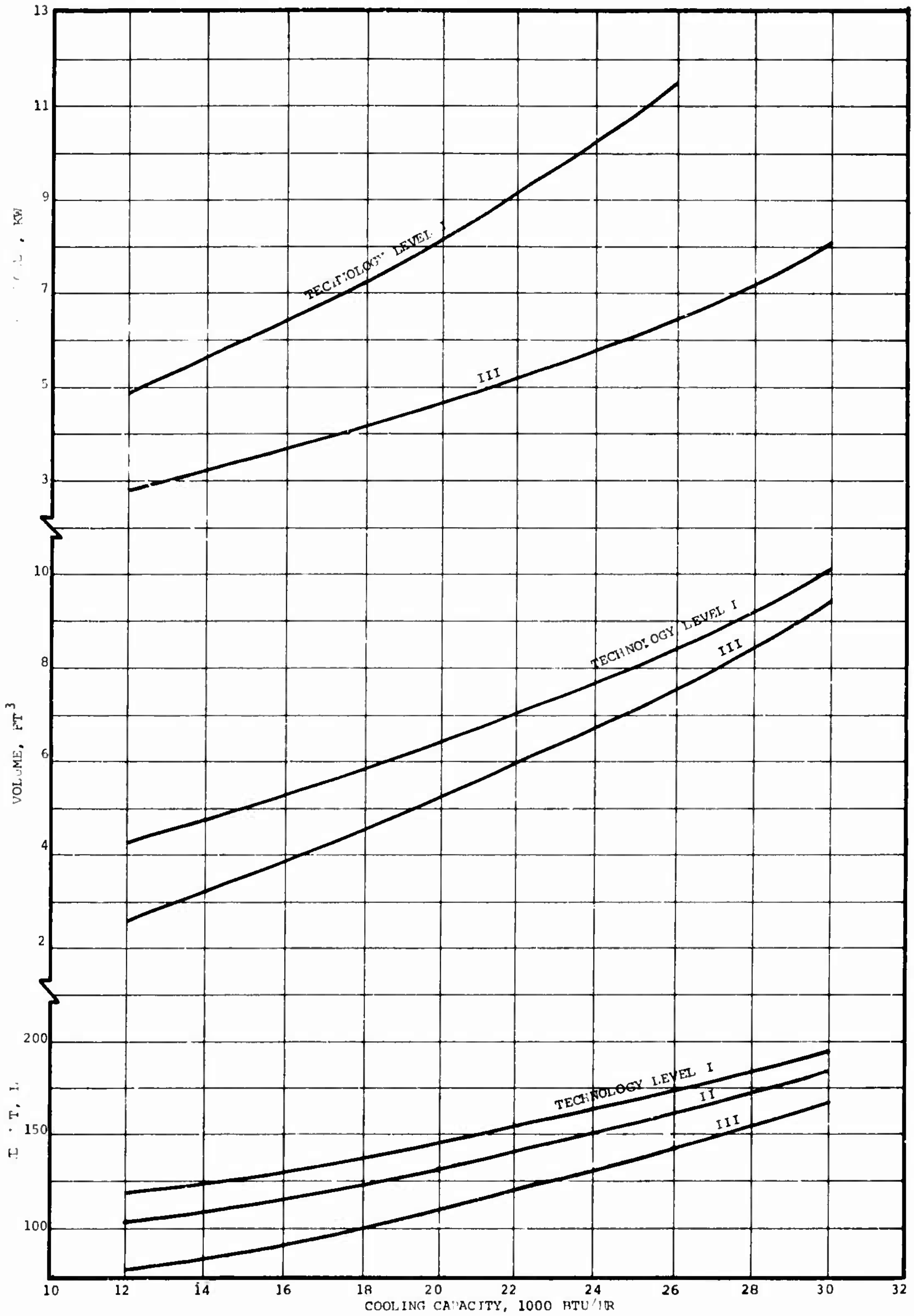


Figure 48. Vapor Cycle ECS Weight, Volume, and Design.

One of the major drawbacks of the vapor cycle unit is the lack of means to heat the cockpit. Present Freons cannot be exposed to surface temperatures in excess of 300°F, but if a refrigerant were developed which could stand 700° to 800°F, a bypass valve arrangement and a coil heat exchanger (recovering gas turbine exhaust heat) could be used for cabin heating. Reverse-flow Freon systems (similar to the commercial heat pump) have been used but have not proven satisfactory for heating operations, since their effectiveness diminishes with decreasing ambient temperature. Thus, all vapor cycle systems must be supplemented with electric heaters, combustion heaters, compressor bleed-air extractions, or exhaust gas turbine heat exchangers for compartment heating.

Combustion heaters are not only heavier, but service experience has proven that this type of system is less reliable than other methods. Compressor bleed-air extraction is the lightest and simplest heating system to use in conjunction with vapor cycle systems. These require the addition of bleed-air ducting and a temperature modulating valve regulated by the cockpit temperature control system. A high-limit duct thermoswitch is activated to protect the cockpit and the passenger compartment from excessive temperatures.

6.6.3 Air-Cycle Systems

Both simple and bootstrap cycles were evaluated to determine the optimum air-cycle ECS for this application. Bootstrap systems evaluated include three- and two-wheel types. The three-wheel is shown schematically in Figure 49. Possible simplifications of this system include deletion of the precooler and the substitution of an electrically driven fan or an eductor to induce the cooling airflow.

The bootstrap system precools the bleed-air in the heat exchanger, compresses it, and takes more heat out of the air that passes through the heat exchanger, prior to expansion through the turbine. This arrangement is desirable when bleed-air pressure ratios are low (less than 3.0:1), since the compressor raises the pressure to more efficient levels for the turbine, as well as provides further cooling in the heat exchanger. Inherently, the system operating efficiency is always higher than a simple air cycle but at the expense of added weight and volume.

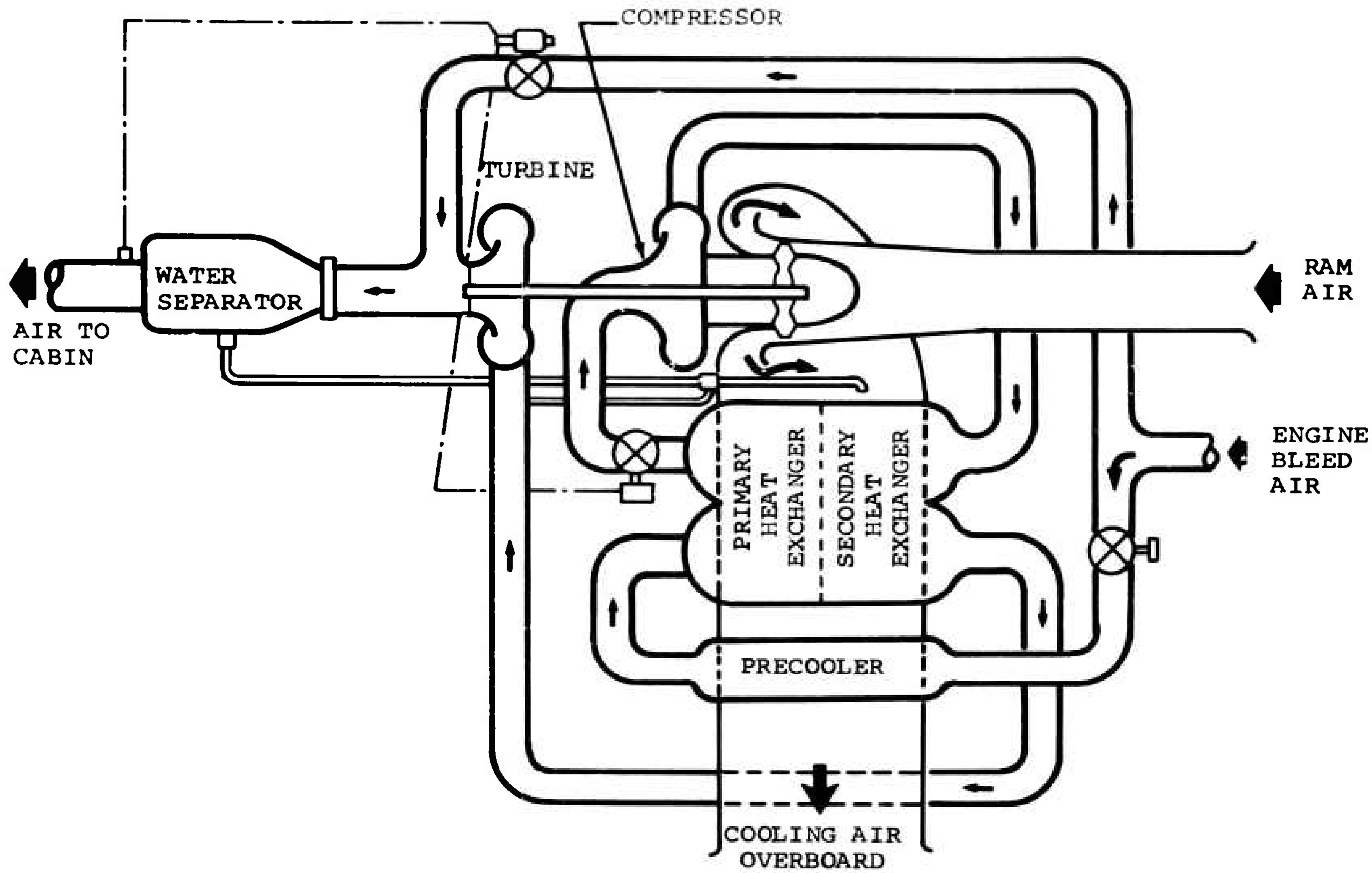


Figure 49. Typical Three-Wheel Bootstrap Air Cycle ECS.

Simple-cycle systems differ from the bootstrap in that there is no compressor; the turbine drives only a cooling fan. The simple-cycle system shown in Figure 50 is recommended for this application. It was chosen for simplicity, light weight, reliability, lower cost, lower vulnerability, and suitability for the pressure ratios available.

This recommended system differs from the conventional in several respects; a reheat-condenser, a jet pump, and recirculation air are included. These items not only increase the efficiency of the unit and reduce weight, but also increase reliability and decrease maintenance requirements. The operation of the recommended system, therefore, has several unique features.

Bleed-air extracted from the air source first passes through a venturi located near or on the engine bleed-air port, which limits the maximum bleed airflow. The size of the venturi is dependent upon engine and ECS cooling requirements. Downstream from the venturi, the airflow is routed through a system shutoff and pressure regulator valve.

The bleed-air is cooled almost to ram air temperature in the high effectiveness ram air heat exchanger. Additional cooling to well below ram air temperature is achieved in the reheat-condenser, where the bleed-air is regeneratively cooled by cold turbine discharge air recirculated by the jet pump. Because of the high pressure and moderate temperature bleed-air conditions in the reheat-condenser, the bleed-air is usually cooled below dew-point, and moisture condenses from the air on baffles inside the reheat-condenser outlet and sprayed into the ram air inlet of the heat exchanger, where it re-evaporates and cools the ram air.

The cool high-pressure bleed-air leaving the reheat-condenser is then expanded through the cooling turbine, and the temperature is further reduced by expansion. The shaft energy produced in the turbine drives a fan that induces the ram cooling airflow across the heat exchanger.

Air leaving the turbine enters the primary nozzle of a jet pump where it induces the regenerative airflow across the cold side of the reheat-condenser. This regenerative flow comes from the supply duct that passes through the reheat-condenser, cools bleed-air, and then mixes with cold turbine discharge air in the jet pump. If the turbine discharge air contains entrained moisture, a large part of the heat transfer in the reheat-condenser may cause the latent heat of vaporization associated with condensing moisture on the bleed-air side and

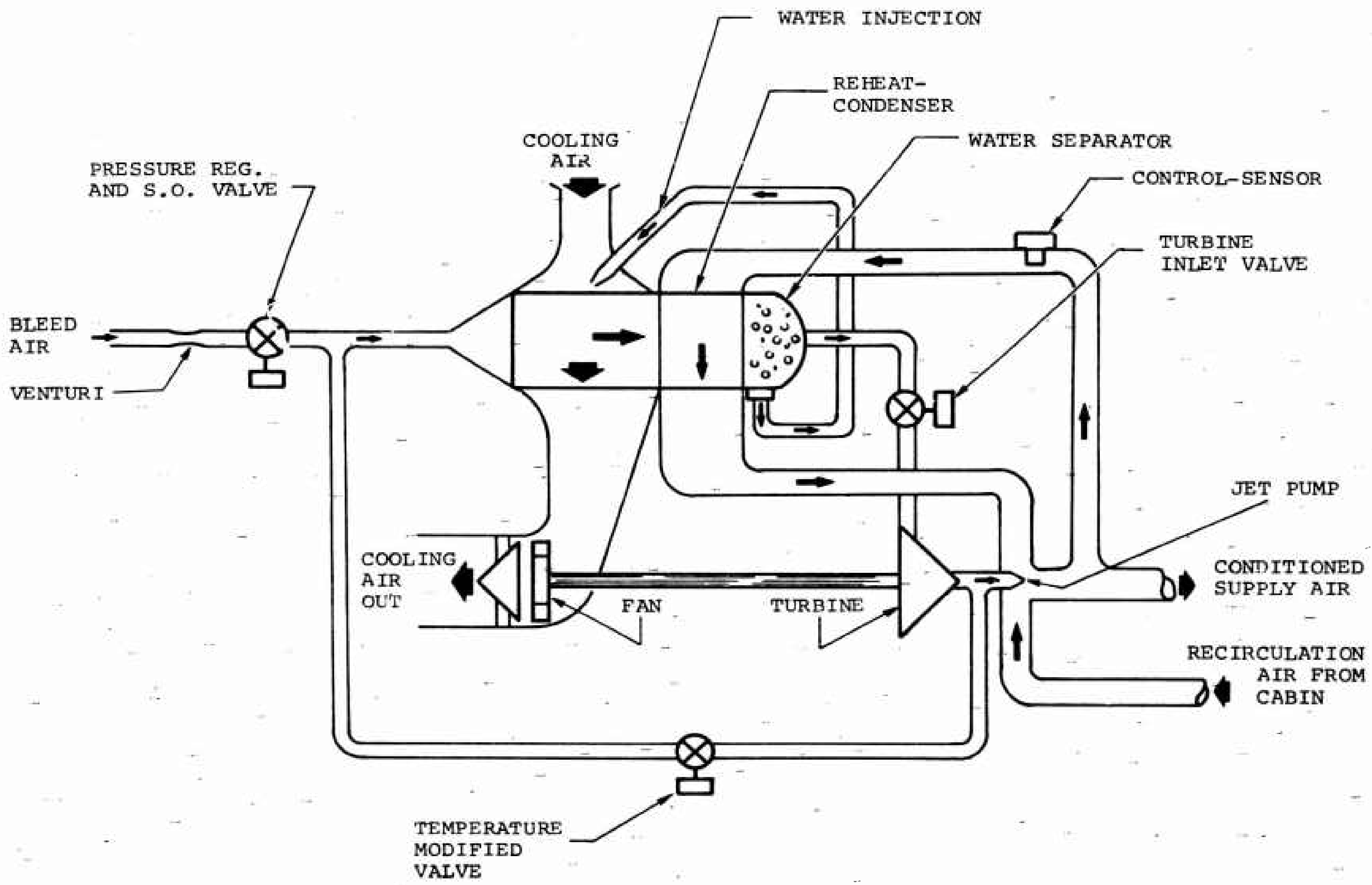


Figure 50. Recommended Simple Air Cycle ECS.

evaporating moisture of the regenerative-air side. Sensible heat transfer may be only a small portion of the total transfer between the two air streams.

From the jet pump exit, the air is supplied to the crew compartment heating and cooling distribution system. The supply air temperature is controlled to a value within the nominal range of 35° to 180°F. This is accomplished by a control subsystem consisting of an integral control-sensor unit, a hot air bypass valve, and a turbine inlet modulating valve mounted within the ECS package. A temperature selector is mounted on the pilot instrument panel and is set by the pilot to the desired temperature.

In some systems, precoolers are used (as in the bootstrap system shown in Figure 49) when the bleed-air temperature is too high for aluminum (above 640°F). The precooler should be as near the engine as possible, to keep the duct temperature as low as possible.

Temperature, pressure, and flow controls are required in all air cycle systems to minimize the bleed airflow penalty and to provide system flexibility over the flight envelope. The weight, volume, and bleed airflow required are shown in Figure 51 for the simple-cycle system.

6.6.4 ECS Study Conclusions

The study revealed that the vapor cycle ECS weight and volume would not be competitive with the air cycle systems. The study also indicated that the combined weight of the air cycle system and the fuel required to furnish bleed-air power is less than the combined weight of the vapor cycle system, the fuel required to furnish power, and the extra weight of a heating system. This is caused, in part, by the high infiltration rate into helicopter cabins. The cooling load for the air cycle systems is not affected by infiltration as severely as is the vapor cycle system, since the air cycle flow is not recycled but tends to pressurize the cockpit. For a vapor cycle system to be competitive with an air cycle system from a weight and volume standpoint, the cockpit infiltration must be held to a minimum, so that 50 to 80 percent recirculating air can be used. The reliability, maintainability, and vulnerability of air cycle systems are also considered much better than those for vapor cycle systems, especially since small, lightweight, vapor cycle systems for aircraft do not exist today.

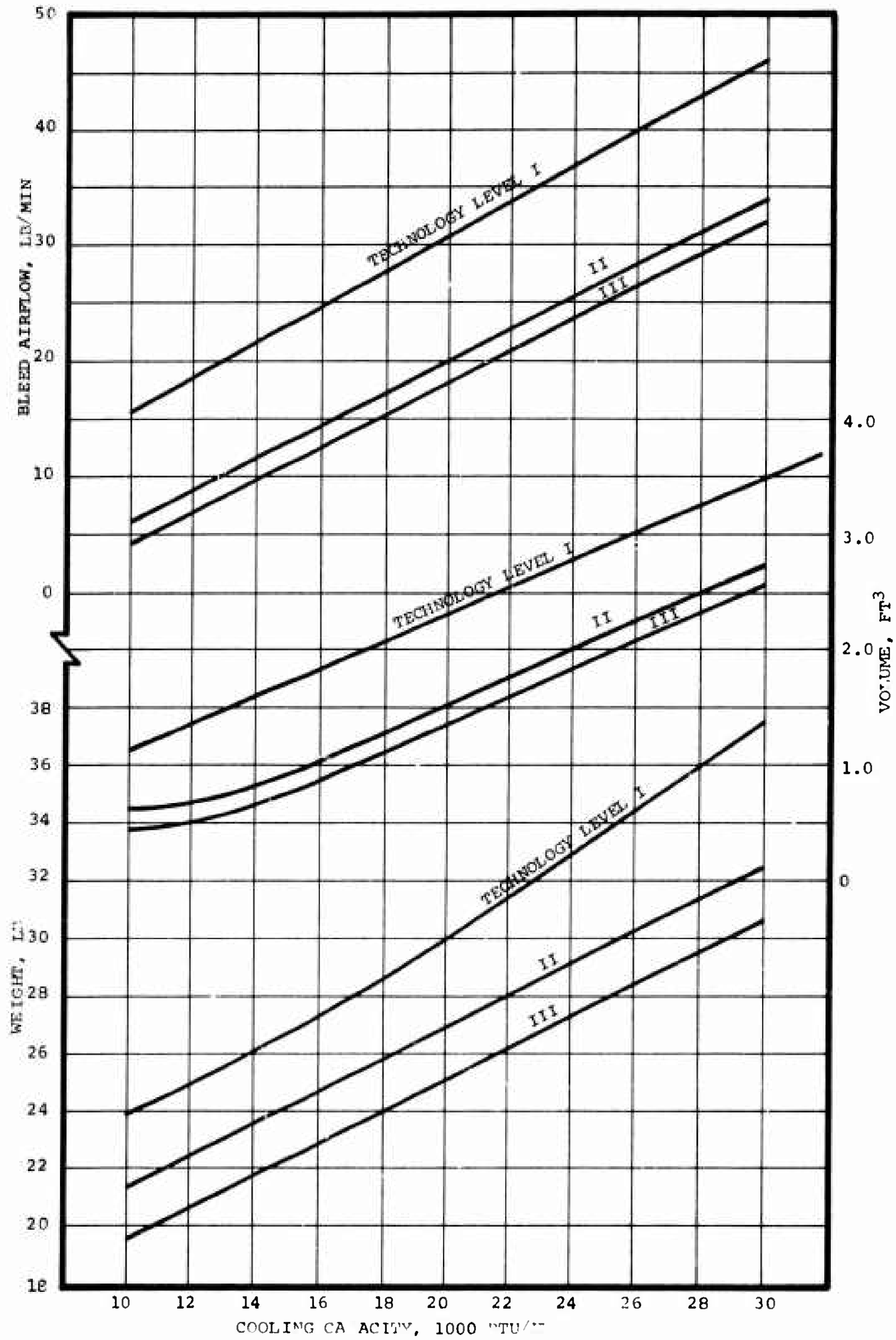


Figure 51. Weight, Volume, and Power of Air Cycle ECS.

Increasing the pressure of the working fluid tends to lower the weight and volume of both types of systems. However, increasing the refrigerant pressure in the vapor cycle severely lowers the efficiency of the system, whereas little change is encountered when the air cycle pressure is increased. In fact, the best turbine efficiencies are usually obtained if pressure ratios above 3.0:1 are maintained. Since the bootstrap system is most efficient when the bleed-air supply pressure ratio is less than 3.0:1 and the available pressure ratio is always higher, the simple-cycle bleed-air system was chosen for the SPS analysis.

6.6.5 Heating and Ventilating Systems

The basic secondary power system was required for ventilation of the cockpit, cabin, and avionics compartment. A refrigeration ECS was an optional item added to the basic systems to determine any penalty to the aircraft. However, a heating system was necessary in all SPS's to provide a 40°F cabin/cockpit temperature as the outside air temperature drops to -25°F. To determine system component requirements, it was necessary to include provisions for heating, ventilating, or cooling.

The heating load was between 70,000 to 80,000 Btu/hr, based on estimated dimensions and structure of the cockpit and cabin. For the study, the maximum avionics compartment temperature was established at 160°F; this can be maintained by the use of a ventilating fan to dissipate the 2700-w load at hot-day conditions.

For systems without ECS, the ventilating flows were estimated as follows:

Avionics	270 cfm, 6 in. H_2O
Cockpit	60 cfm, 6 in. H_2O
Cabin	350 cfm, 6 in. H_2O

The type of heaters and ventilating equipment was dependent upon the type of APU. Since the APU provides system power on the ground when the main engines are not in operation, the heating system was directly related to the type of APU power available. For instance, bleed type APU's can provide pressurized warm air, which could be conveniently used in a simple ejector or jet pump system (Figure 52). This was designated as a bleed- air heater. In operation, the bleed-air provides the primary airflow in the ejector, which induces a secondary

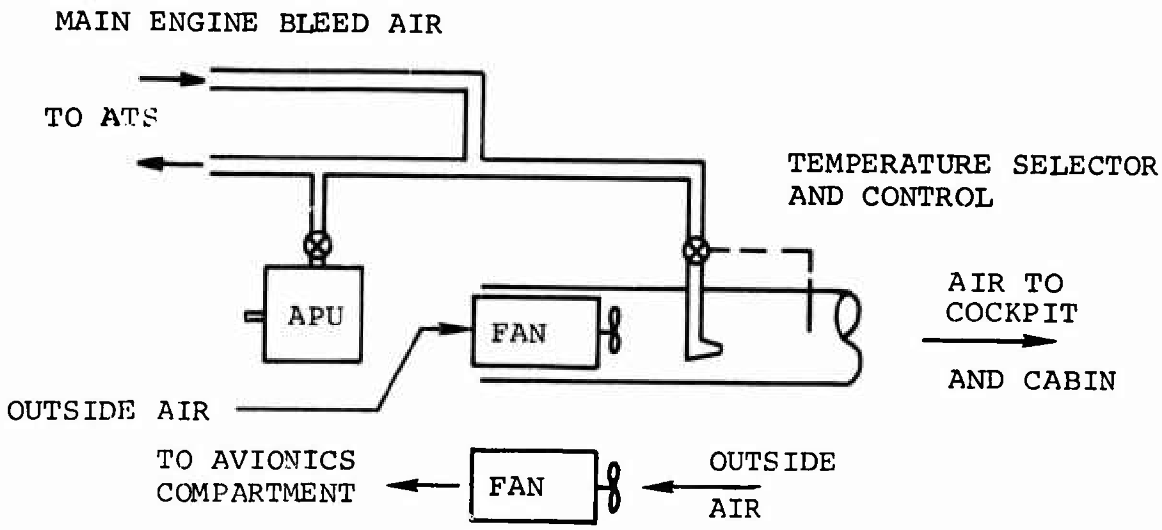


Figure 52. Heating and Ventilating Schematic, Systems With Bleed-Type APU.

flow of recirculated cabin air that mixes with the warm air to provide the required temperature. A temperature regulating and selector control was included that senses the mixed air temperature and regulates the hot airflow by means of a modulating pneumatic valve. The bleed-air heater is operable from the APU on the ground or from main engine bleed-air in flight; the electric-motor-driven heater fan may be used for ventilation. A separate fan was included for ventilation of the avionics compartment.

For systems with a shaft-power-only APU and no air compressor, it was necessary to provide a combustion heater. The heater and fan assembly (Figure 53) can provide both heat and ventilation to the cockpit and cabin and is operable on the ground and in flight. All necessary components for installation in the aircraft, such as fans, controls, fuel pump, filters, valves, ignition unit switches, flanges, and clamps are included in the heater unit weight and size. An installation factor was included to account for ducting, mounts, cockpit controls, etc. Several candidate systems with a shaft-power APU had an air compressor driven by the APU. These systems had only a bleed-air heater.

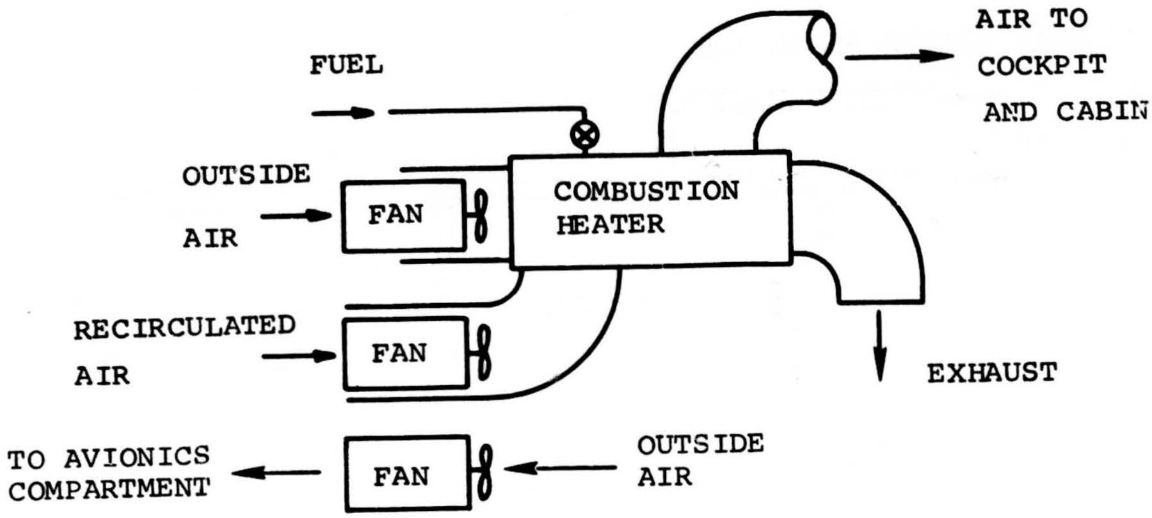


Figure 53. Heating and Ventilating Schematic, Systems Without ECS and Without a Compressed Air Source.

An alternate heating system investigated for a shaft power APU was an exhaust heat exchanger. In this system, the heat exchanger would be installed around the APU exhaust through which the cabin air could be ducted. This could provide sufficient heating when the APU was operated, but in flight a bleed-air heater operated by main-engine bleed-air had to be included. The combined weight of these components was slightly greater than that of the combustion heater system. An APU exhaust heater, however, would be a convenient method of supplementing bleed-air heater systems for extreme low-temperature conditions, when a system employing a bleed-air heater could produce additional heating. This would be particularly applicable to Technology Level III where less APU bleed-air was available because of reduced cooling and engine starting requirements.

When the air cycle environmental control system was added to a baseline system, the heater was removed, since the ECS package was capable of supplying both cooling and heating (Figure 54). This dual function is accomplished automatically by the temperature regulating and selector control. The refrigeration unit includes a hot air bypass which mixes the hot air with cooled air to obtain the desired discharge air temperature. The system is operable from APU or main engine bleed air. Avionic compartment cooling is obtained by ducting the relatively cool cockpit air to the compartment. A fan in the avionics

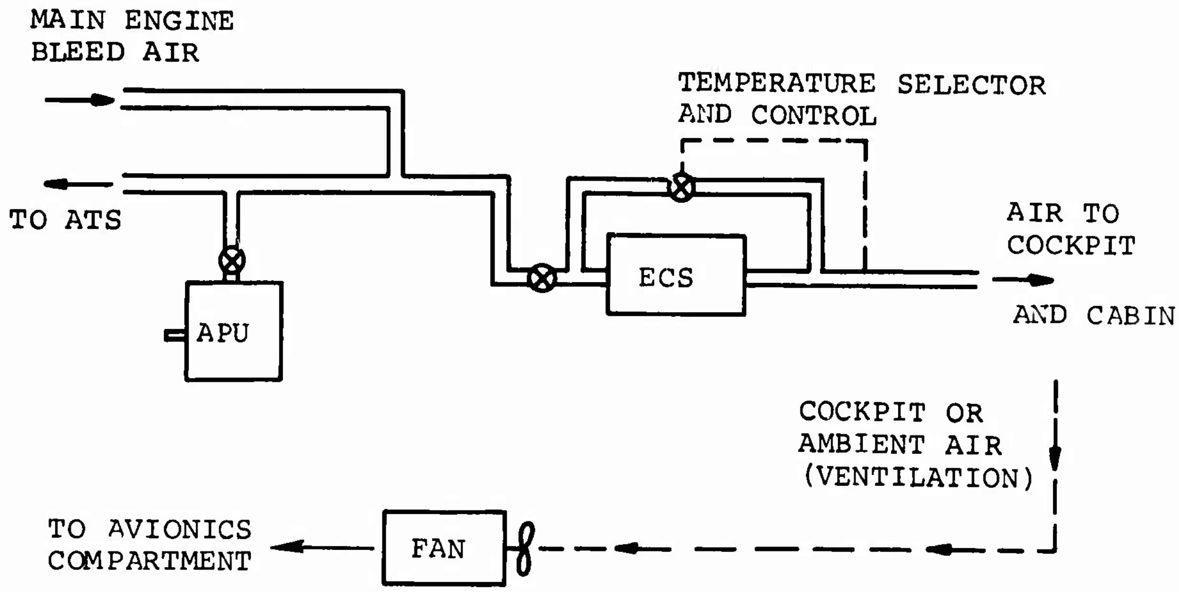


Figure 54. Heating and Ventilating Schematic, Systems With Air Cycle ECS.

compartment was maintained to ensure a flow of cooling air under normal conditions and in case of leakage from battle damage to the cockpit.

The weights and volumes of all heater systems are included in Table XXIV.

6.7 APU

The APU analysis is dependent upon the definition of the duty cycle of the secondary power system and the power requirements of each candidate system. These criteria define the general power range of the APU. The APU power class influences cycle assumptions such as component efficiencies, cooling flows, and pressure drops. When the cycle assumptions were defined, a study was conducted for a range of cycle parameters. The main purpose of the parametric study was to define the optimum APU cycles and configuration for this applicaton. Normalized APU off-design performance curves for various configurations were generated for the study. Performance and weight/volume data for the selected cycles/configuration were calculated for the power class range of the APU. These data were used in the systems comparison analysis, and various APU starting systems were evaluated (Section 8.4).

TABLE XXIV. HEATER SYSTEM WEIGHTS AND VOLUMES*						
Technology Levels	I		II		III	
	lb	ft^3	lb	ft^3	lb	ft^3
Bleed Air Heater (includes ejector, primary air shutoff and regulating valve, temperature controls, electric motor-driven blower)	13.5	0.19	13.5	0.19	12	0.19
Combustion Heater (includes basic heater, two blowers, fuel controls, fuel pump, filter, ignition, switch, duct flanges, clamps, plenum)	58.5	2.10	58.5	2.10	53	1.90
ECS (Refrigeration and Heating (Section 6.6)	27	1.70	24	0.90	22	0.75

*Values shown for weight and volume do not include installation. A weight installation factor of 1.35 was used for all heaters and ECS.

6.7.1 Parametric Cycle Study

Introduction and Summary

The APU parametric cycle study was conducted on the non-regenerated, regenerated, and after-heat cycles. The three technology time periods outlined in Section 1 formed the guidelines for the study.

Component efficiencies, pressure drops, leakages, cooling flow schedules, accessory power, and regenerator effectiveness were

assumed for the selected cycles. With these assumptions, cycle data were generated covering the following parameters:

1. Overall cycle pressure ratios of 4 to 20:1
2. Turbine inlet temperatures of 1600° to 2400°F
3. Bleed-air pressure ratios of 2 to 6:1
4. Regenerator effectiveness of 0.80 to 0.90

Using the parametric data generated, possible APU aerodynamic configurations were matched with the selected cycles and compared, with respect to the following:

1. Performance
   (a) Design
   (b) Off-design
2. Other
   (a) Maintainability
   (b) Reliability
   (c) Complexity
   (d) Vulnerability
   (e) Initial manufacturing cost
   (f) Initial life-cycle cost

Following this comparative analysis, the APU configuration and final cycle parameter ranges were established.

Basic Cycles Considered

Of the three basic cycles considered for the study, the non-regenerated and regenerated are conventional; therefore, considerable test and operational data are available. The after-heat cycle is unique in that the combustor is located behind the turbine section.

Figure 55 is a schematic of a typical non-regenerated cycle for a single-shaft APU. The non-regenerated cycle has the best specific power and SFC, normally at higher pressure ratios than the other two cycles.

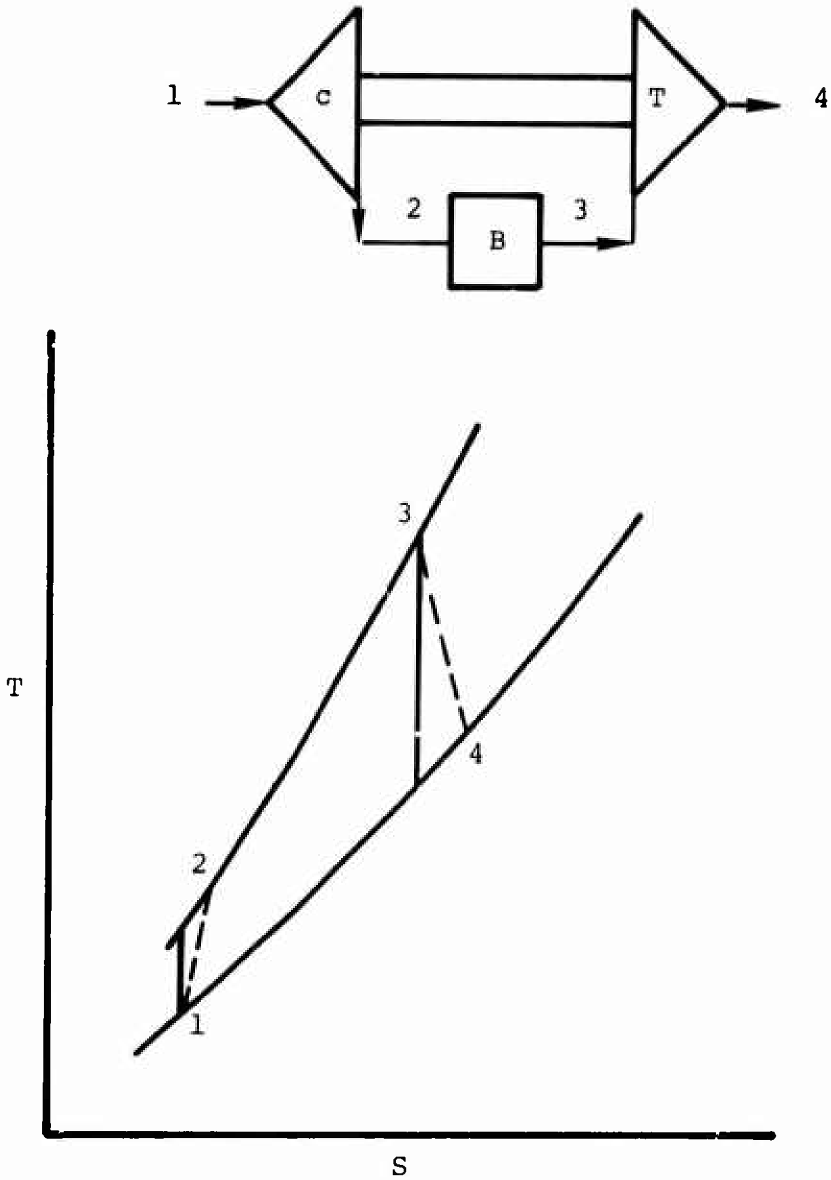


Figure 55. Nonregenerated Cycle Schematic.

Figure 56 shows the basic configuration of the regenerated cycle. The heat exchanger may be either a rotary regenerator or a fixed-boundary recuperator. The inherently higher efficiency of regenerated cycles permits SFC optimization at lower turbine inlet temperatures and cycle pressure ratios. The regenerated cycle will exhibit lower fuel consumption than the non-regenerated cycles. However, the size and weight of the regenerated are higher than those of the non-regenerated cycles.

A typical after-heat cycle example is shown in Figure 57. It is a regenerative type, with the burner and turbine positions reversed in the flow path. The optimum fuel consumption is between the regenerated and non-regenerated cycles. The principal advantage is that clean air, rather than the products of combustion, is permitted to enter the turbine section. The size and weight of the after-heat configurations are larger than those of the regenerated cycles.

Cycle Assumptions

Establishing cycle assumptions for the parametric study necessitated a review of the present technology (Technology Level I) and an extension of this to Technology Levels II and III. The cycle assumptions are representative of the size of turbomachinery being analyzed in this study. Tables XXV through XXXIII summarize the assumptions.

Parametric Cycle Data

From the assumptions listed in the previous section, parametric cycle data were generated by using a design-point component matching program. Several useful parametric quantities, such as specific horsepower and SFC, are obtained from this program.

The ranges of cycle parameters covered in this study are:

APU eshp	30 to 120
Cycle pressure ratio	4 to 20
Turbine inlet temperature	1600° to 2400°F
Bleed-air pressure ratio	2 to 6
After-heat cycle rotary regenerator effectiveness	0.85 to 0.95
Conventional regnerated cycle heat exchanger effectiveness	0.8 to 0.9

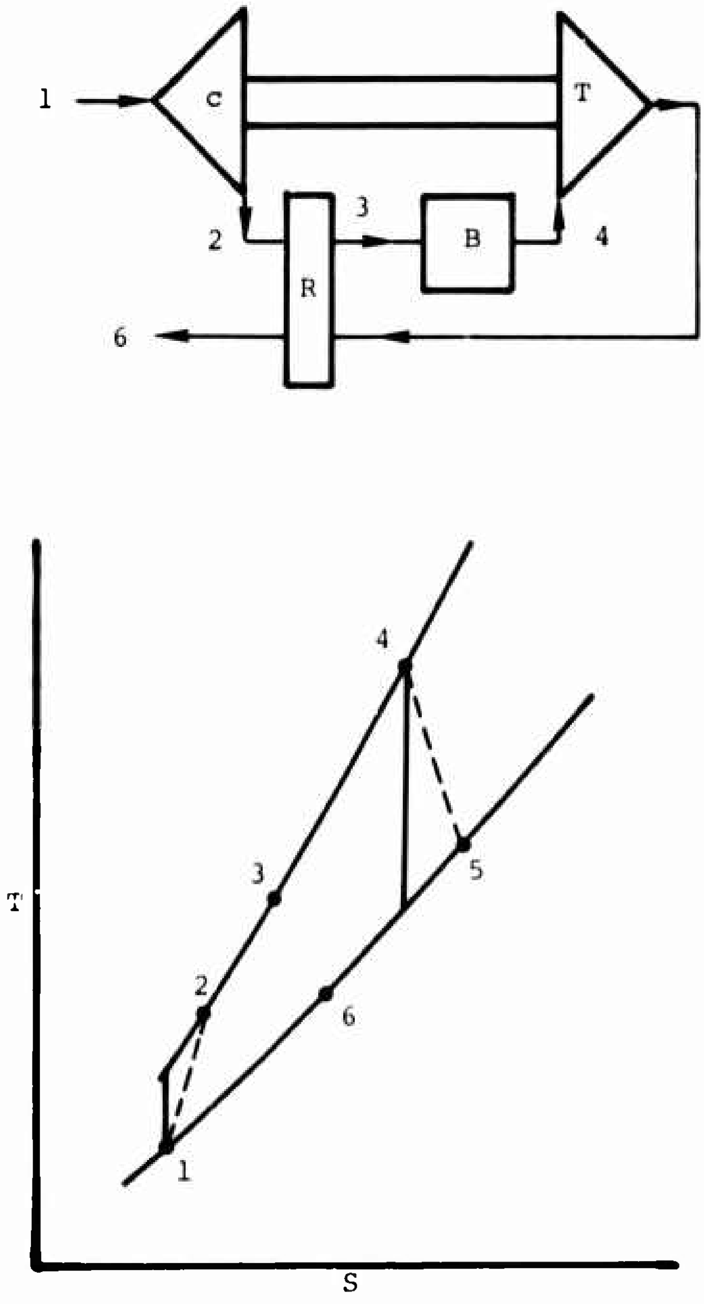


Figure 56. Regenerated Cycle Schematic.

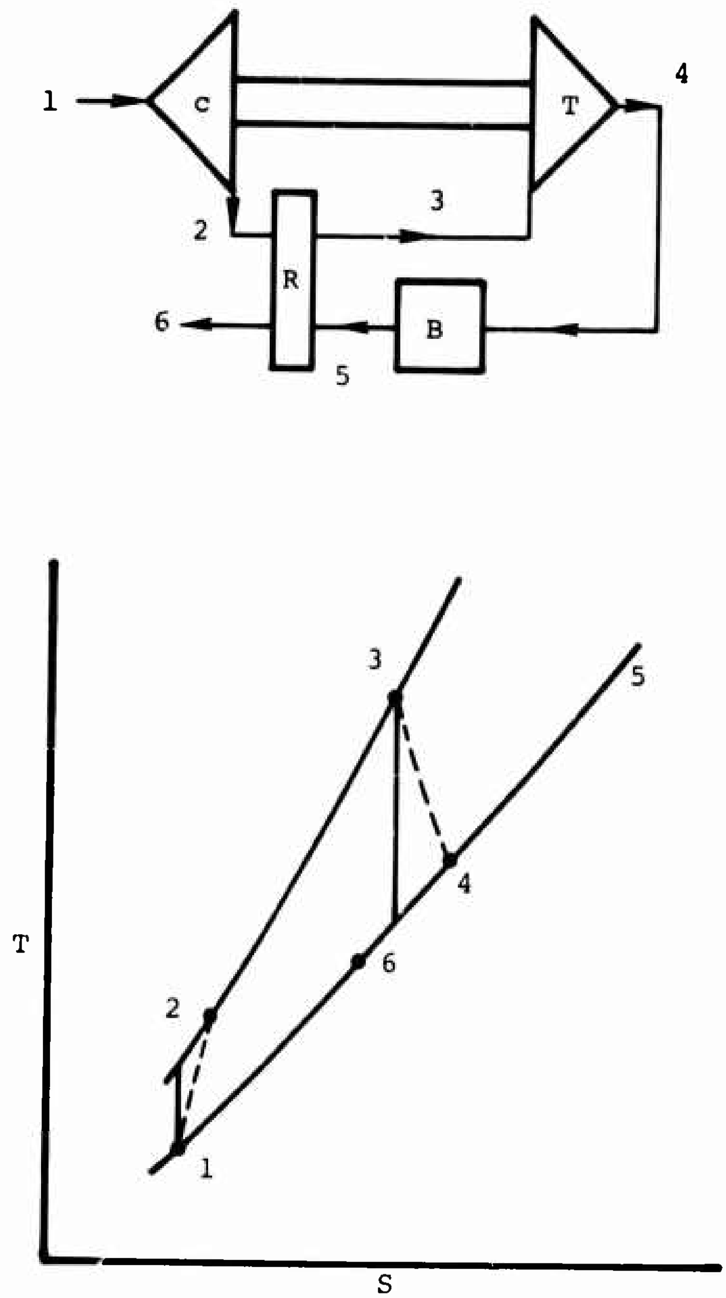


Figure 57. After-Heat Cycle Schematic.

TABLE XXV. BASIC CYCLE ASSUMPTIONS

Characteristics	Technology Level I	II	III
Ambient temperature, °F	130	130	130
Ambient pressure, psia	14.7	14.7	14.7
Range of eshp, hr	30 to 115	30 to 115	30 to 115
Mechanical efficiency	0.98	0.98	0.98
Accessory horsepower/ equivalent shaft horsepower	0.06	0.05	0.04
Burner efficiency	0.98	0.985	0.99
Compressor leakage	0.005	0.005	0.005
Burner leakage	0.005	0.005	0.005

TABLE XXVI. COMPONENT PRESSURE DROPS			
	Technology Level		
Component	I	II	III
Inlet	0.025	0.025	0.025
Compressor discharge	0.015	0.015	0.015
Burner	0.050	0.045	0.040
Exhaust diffuser	0.060	0.060	0.0

TABLE XXVII. COOLING FLOW SCHEDULES, PERCENT			
	Technology Level		
TIT, °F	I	II	III
1600	0.0	0.0	Uncooled
1700	1.0	0.5	Uncooled
1800	2.0	1.0	Uncooled
1900	3.0	1.5	Uncooled
2000	4.0	2.0	Uncooled
2100	5.0	2.5	Uncooled
2200	6.0	3.0	Uncooled
2300	7.0	3.5	Uncooled
2400	8.0	4.0	Uncooled

TABLE XXVIII. TURBINE EFFICIENCY SCHEDULE

Tech Level	TIT \ P/P	2	4	6	8	10	12	14	16	18	20
I	1600	0.880	0.878	0.876	0.874	0.872	0.870	0.868	0.866	0.864	0.862
	1700	0.879	0.877	0.875	0.873	0.871	0.869	0.867	0.865	0.863	0.861
	1800	0.878	0.876	0.874	0.872	0.870	0.868	0.866	0.864	0.862	0.860
	1900	0.877	0.875	0.873	0.871	0.869	0.867	0.865	0.863	0.861	0.859
	2000	0.876	0.874	0.872	0.870	0.868	0.866	0.864	0.862	0.860	0.858
	2100	0.875	0.873	0.871	0.869	0.867	0.865	0.863	0.861	0.859	0.857
	2200	0.874	0.872	0.870	0.868	0.866	0.864	0.862	0.860	0.858	0.856
	2300	0.873	0.871	0.869	0.867	0.865	0.863	0.861	0.859	0.857	0.855
	2400	0.872	0.870	0.868	0.866	0.864	0.862	0.860	0.858	0.856	0.854
II	1600	0.895	0.893	0.891	0.889	0.887	0.885	0.883	0.881	0.879	0.877
	1700	0.894	0.892	0.890	0.888	0.886	0.884	0.882	0.880	0.878	0.876
	1800	0.893	0.891	0.889	0.887	0.885	0.883	0.881	0.879	0.877	0.875
	1900	0.892	0.890	0.888	0.886	0.884	0.882	0.880	0.878	0.876	0.874
	2000	0.891	0.889	0.887	0.885	0.883	0.881	0.879	0.877	0.875	0.873
	2100	0.890	0.888	0.886	0.884	0.882	0.880	0.878	0.876	0.874	0.872
	2200	0.889	0.887	0.885	0.883	0.881	0.879	0.877	0.875	0.873	0.871
	2300	0.888	0.886	0.884	0.882	0.880	0.878	0.876	0.874	0.872	0.870
	2400	0.887	0.885	0.883	0.881	0.879	0.877	0.875	0.873	0.871	0.869
III	1600	0.910	0.908	0.906	0.904	0.902	0.900	0.898	0.896	0.894	0.892
	1700	0.909	0.907	0.905	0.903	0.901	0.899	0.897	0.895	0.893	0.891
	1800	0.908	0.906	0.904	0.902	0.900	0.898	0.896	0.894	0.892	0.890
	1900	0.907	0.905	0.903	0.901	0.899	0.897	0.895	0.893	0.891	0.889
	2000	0.906	0.904	0.902	0.900	0.898	0.896	0.894	0.892	0.890	0.888
	2100	0.905	0.903	0.901	0.899	0.897	0.895	0.893	0.891	0.889	0.887
	2200	0.904	0.902	0.900	0.898	0.896	0.894	0.892	0.890	0.888	0.886
	2300	0.903	0.901	0.899	0.897	0.895	0.893	0.891	0.889	0.887	0.885
	2400	0.902	0.900	0.898	0.896	0.894	0.892	0.890	0.888	0.886	0.884

TABLE XXIX. DESIGN-POINT COMPRESSOR EFFICIENCY SCHEDULE

	Technology Level		
P/P	I	II	III
2	0.8022	0.8115	0.8343
4	0.7806	0.7912	0.8090
6	0.7682	0.7797	0.7955
8	0.7596	0.7717	0.7877
10	0.7527	0.7653	0.7822
12	0.7466	0.7598	0.7780
14	0.7409	0.7545	0.7744
16	0.7355	0.7496	0.7702
18	0.7302	0.7447	0.7681
20	0.7250	0.7400	0.7650

TABLE XXX. HEAT EXCHANGER LEAKAGES

	Technology Level		
P/P	I	II	III
2	0.011	0.009	0.007
4	0.012	0.010	0.008
6	0.013	0.011	0.009
8	0.014	0.012	0.010
10	0.015	0.013	0.011
12	0.016	0.014	0.012
14	0.017	0.015	0.013
16	0.018	0.016	0.014
18	0.019	0.017	0.015
20	0.020	0.018	0.016

TABLE XXXI. HEAT EXCHANGER PRESSURE DROPS (ALL TECHNOLOGY LEVELS)

ε_r	Total ($\Delta P/P$)	Cold Side ($\Delta P/P$)	Hot Side ($\Delta P/P$)
0.80	0.050	0.0125	0.0375
0.85	0.055	0.01375	0.04125
0.90	0.060	0.0150	0.0450

TABLE XXXII. DESIGN POINT FOR SHAFT POWER CONVERSION TO BLEED FLOW

Conversion	Bleed (P/P)	Technology Level I	II	III
Conventional Bleed Techniques	2	0.8022	0.8115	0.8343
	3	0.7900	0.8000	0.8200
	4	0.7806	0.7913	0.8090
	5	0.7708	0.7894	0.8012
	6	0.7682	0.7797	0.7955
Notched Impeller	2	0.7380	0.7466	0.7676
	3	0.7268	0.7360	0.7544
	4	0.7182	0.7280	0.7443
	5	0.7091	0.7262	0.7371
	6	0.7067	0.7173	0.7319

TABLE XXXIII. DESIGN-POINT LOAD COMPRESSOR EFFICIENCY SCHEDULE

Bleed (P/P)	Bleed (hp)	Technology Level I	Technology Level II	Technology Level III
2	25	0.7722	0.7815	0.8043
	50	0.7822	0.7915	0.8143
	75	0.7922	0.8015	0.8243
	100	0.8022	0.8115	0.8343
	125	0.8122	0.8215	0.8443
	150	0.8222	0.8315	0.8543
3	25	0.7600	0.7700	0.7900
	50	0.7700	0.7800	0.8000
	75	0.7800	0.7900	0.8100
	100	0.7900	0.8000	0.8200
	125	0.8000	0.8100	0.8300
	150	0.8100	0.8200	0.8400
4	25	0.7506	0.7613	0.7790
	50	0.7606	0.7713	0.7890
	75	0.7706	0.7813	0.7990
	100	0.7806	0.7913	0.8090
	125	0.7906	0.8013	0.8190
	150	0.8006	0.8113	0.8290
5	25	0.7408	0.7549	0.7712
	50	0.7508	0.7649	0.7812
	75	0.7608	0.7749	0.7912
	100	0.7708	0.7849	0.8012
	125	0.7808	0.7949	0.8112
	150	0.7908	0.8049	0.8212
6	25	0.7312	0.7142	0.7352
	50	0.7412	0.7242	0.7452
	75	0.7512	0.7342	0.7552
	100	0.7612	0.7442	0.7652
	125	0.7712	0.7542	0.7752
	150	0.7812	0.7642	0.7852

The data were generated, using ambient conditions of 130°F at sea level for the three technology levels.

The parametric data curves are presented in Figures 58 through 72. Figures 58 through 63 are of the SFC and specific horsepower for the non-regenerated, regenerated, and after-heat cycles. Figures 64 through 72 are curves for shaft power conversion to bleed flow. Three methods of producing bleed-air were considered. The conventional method, where the bleed pressure ratio equals the cycle pressure ratio, is presented in Figures 64, 65, and 66. For cycle ratios higher than the desired bleed pressure, a notched impeller (Figure 73) must be used to remove the bleed flow at a lower pressure ratio. The parametric data for the notched impeller are shown in Figures 67, 68, and 69. Load compressor bleed flow to shaft power conversion is included in Figures 70, 71, and 72.

The specific horsepower and SFC curves were used in the selection of the cycle pressure ratio and turbine inlet temperature ranges for the APU. These curves, in conjunction with the shaft power conversion to bleed flow, were generated to aid in establishing size and weight data for the APU.

Candidate Cycle and Configuration Evaluation

The evaluation of the candidate cycles and configurations was based on the ground rules previously established (Section 6), with special emphasis on reliability and maintainability. Based on the experience of the contractor, the performance of the candidate cycles was evaluated against the reliability and maintainability, tempered with consideration of life cost, weight, and volume.

Since performance is an important factor in the cycle/configuration selection, Figure 74 was generated to show the effect of APU configuration on off-design performance. For a given APU configuration, the regenerated type will have a slightly better off-design characteristic than a non-regenerated configuration. This is due to the fact that at off-design operating points, the heat exchanger is oversized, giving increased heat-transfer effectiveness.

Although the normalized off-design characteristic (for a given APU configuration) is similar for regenerated and non-regenerated cycles, the design-point SFC of a regenerated cycle is lower than that of a non-regenerated cycle.

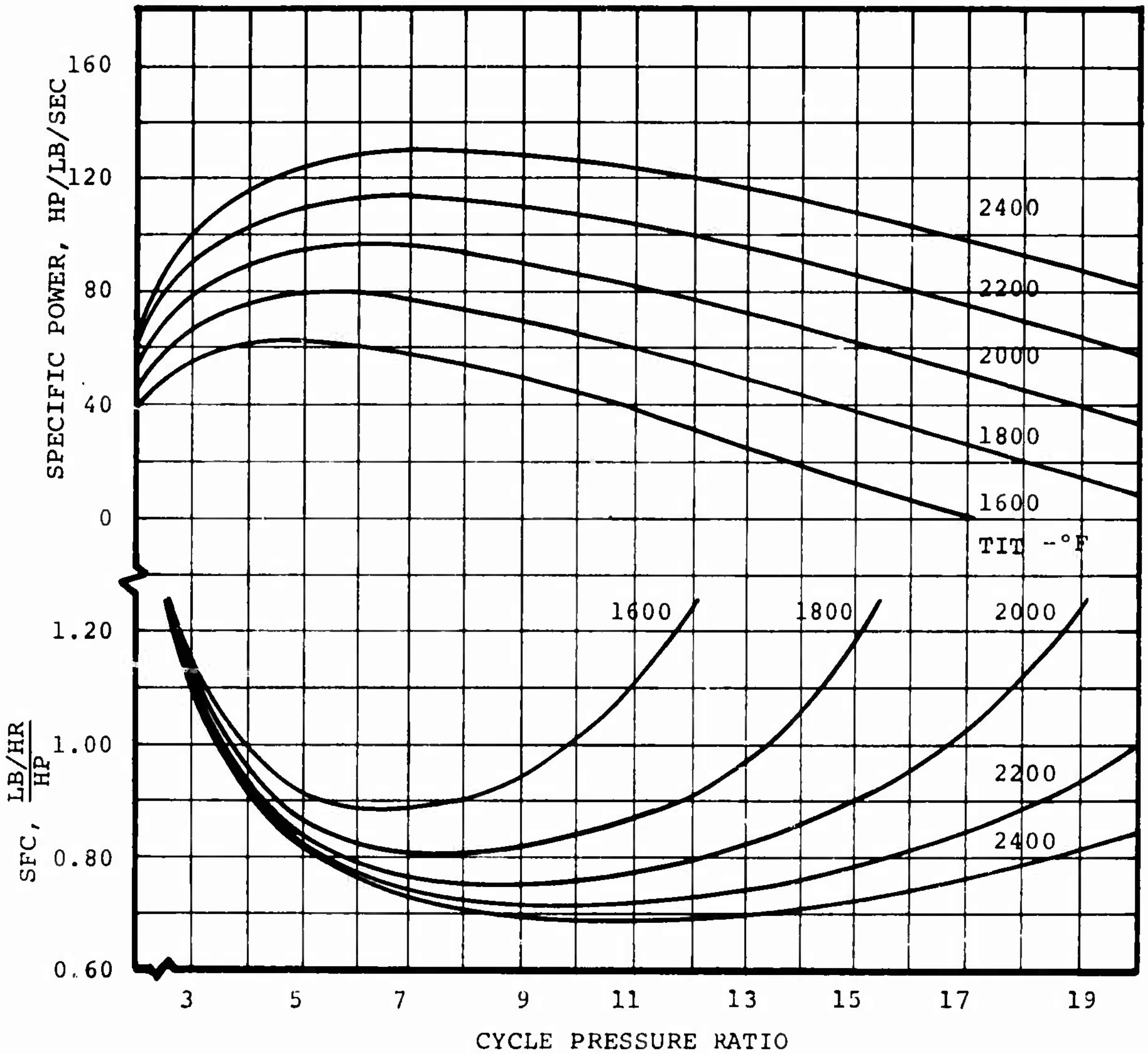


Figure 58. SFC and Specific Horsepower vs Cycle P/P, Nonregenerative, Technology Level I.

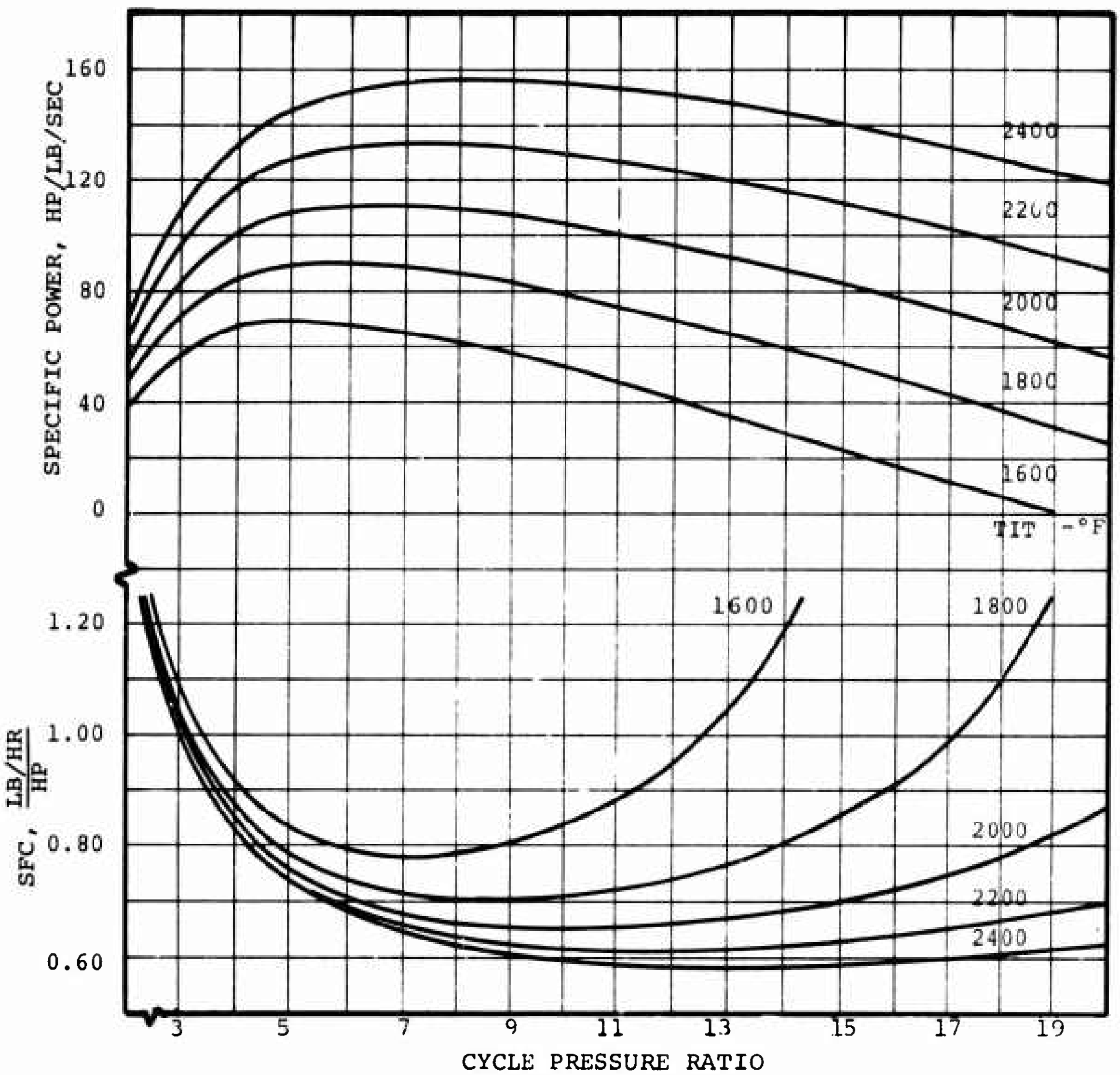


Figure 59. SFC and Specific Horsepower vs Cycle P/P, Nonregenerated, Technology Level II.

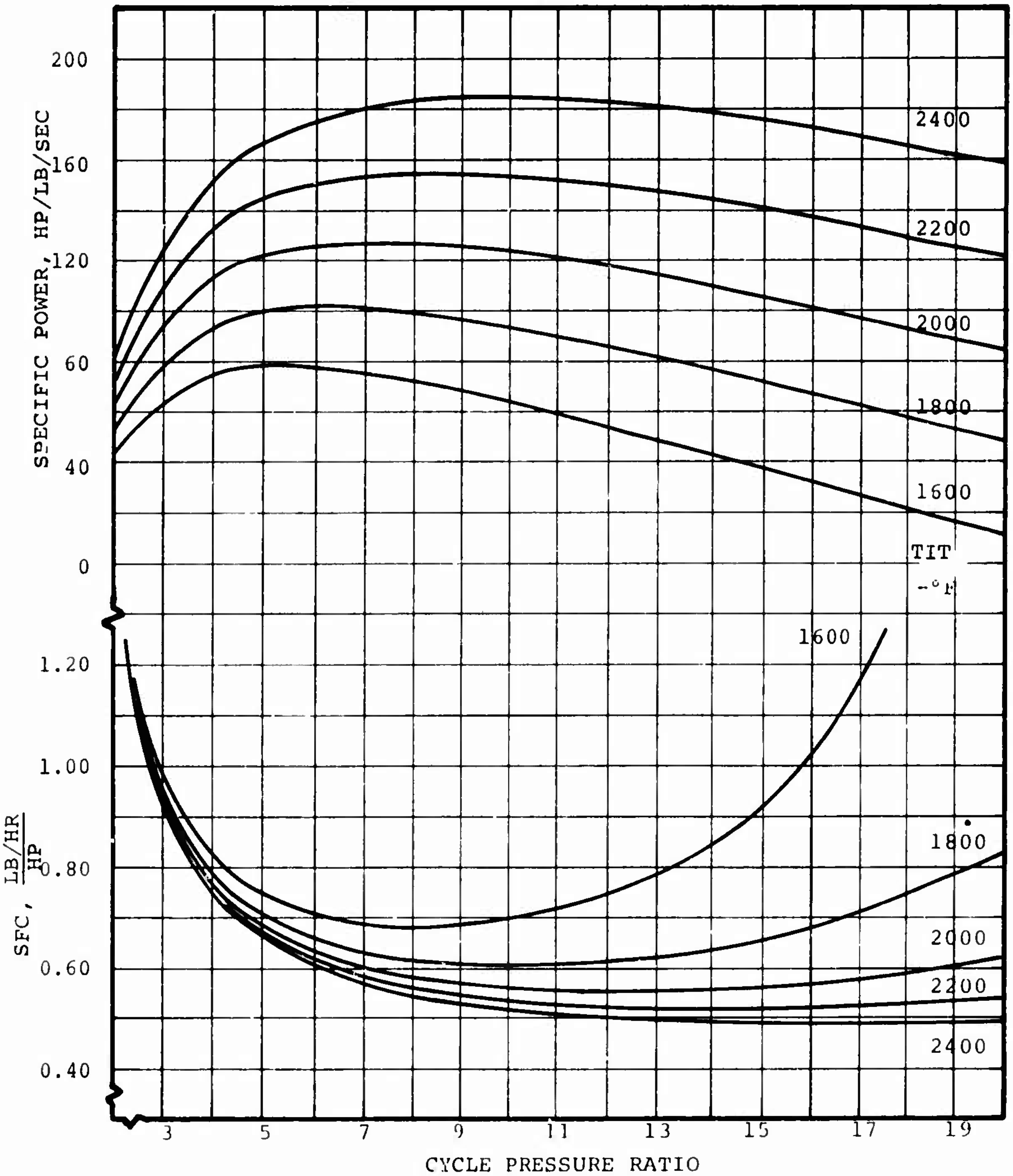


Figure 60. SFC and Specific Horsepower vs Cycle P/P, Nonregenerated, Technology Level III.

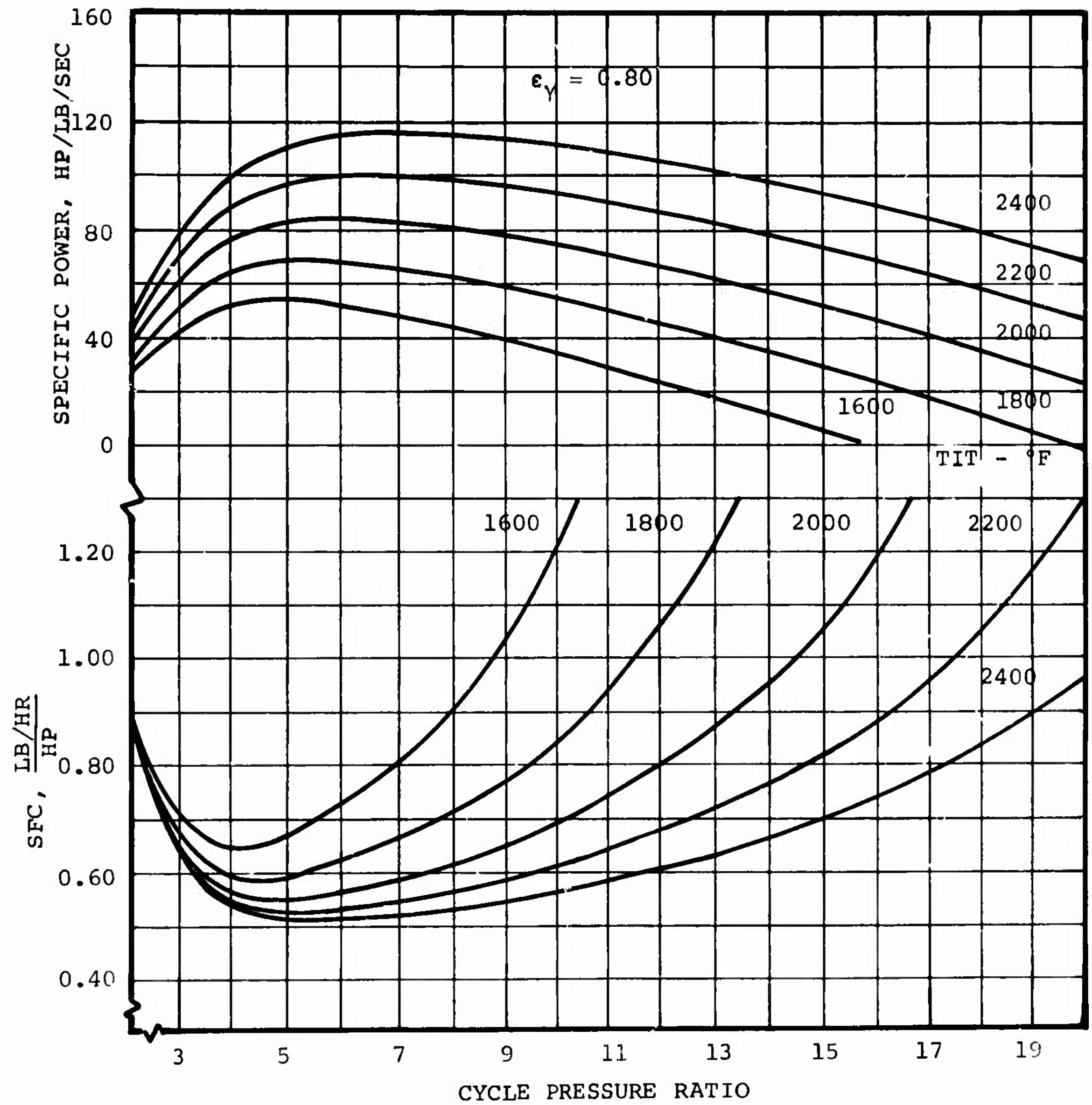


Figure 61. SFC and Specific Horsepower vs Cycle P/P, Regenerative, Technology Level I.

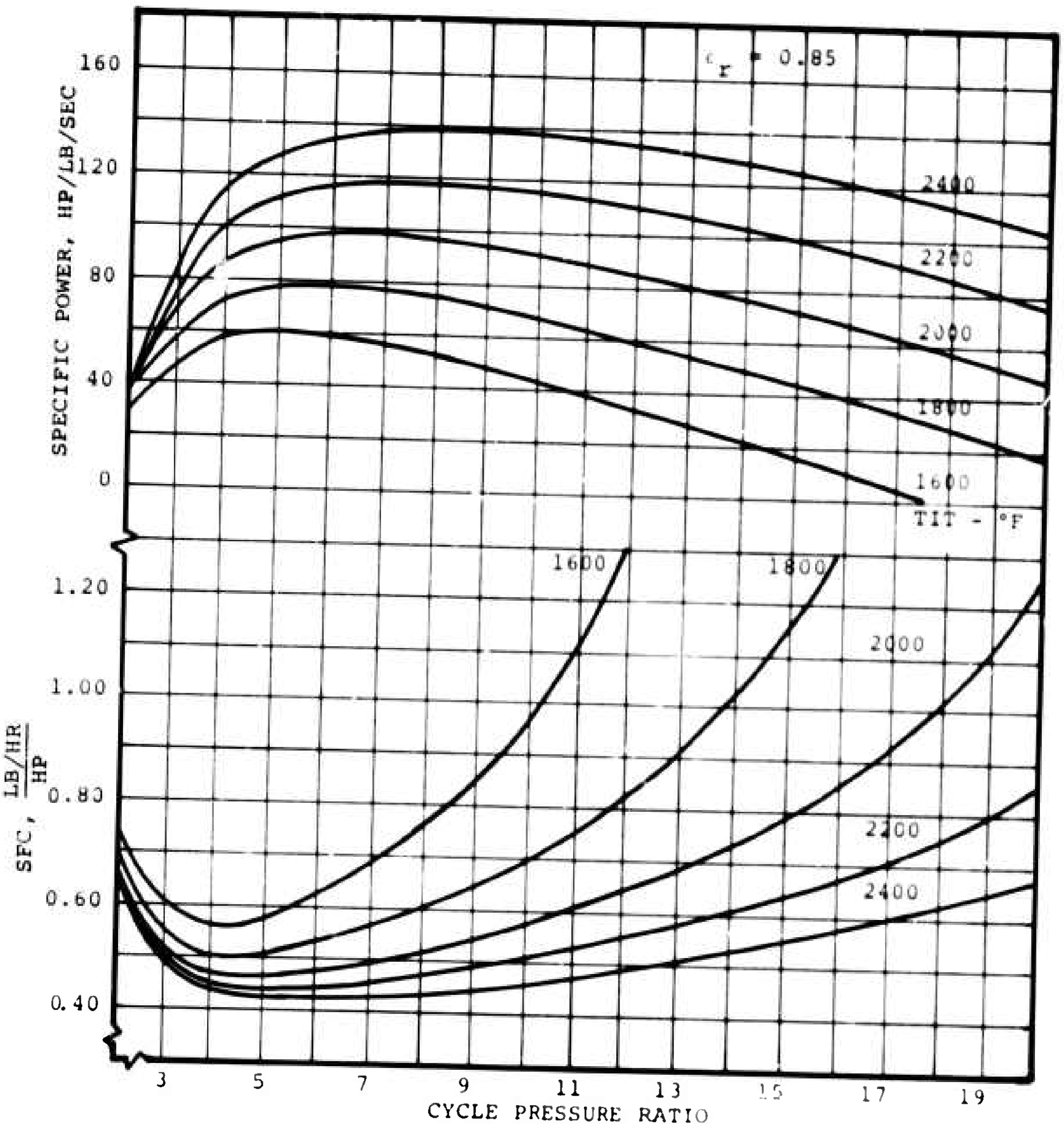


Figure 62. SFC and Specific Horsepower vs Cycle P/P, Regenerative, Technology Level II.

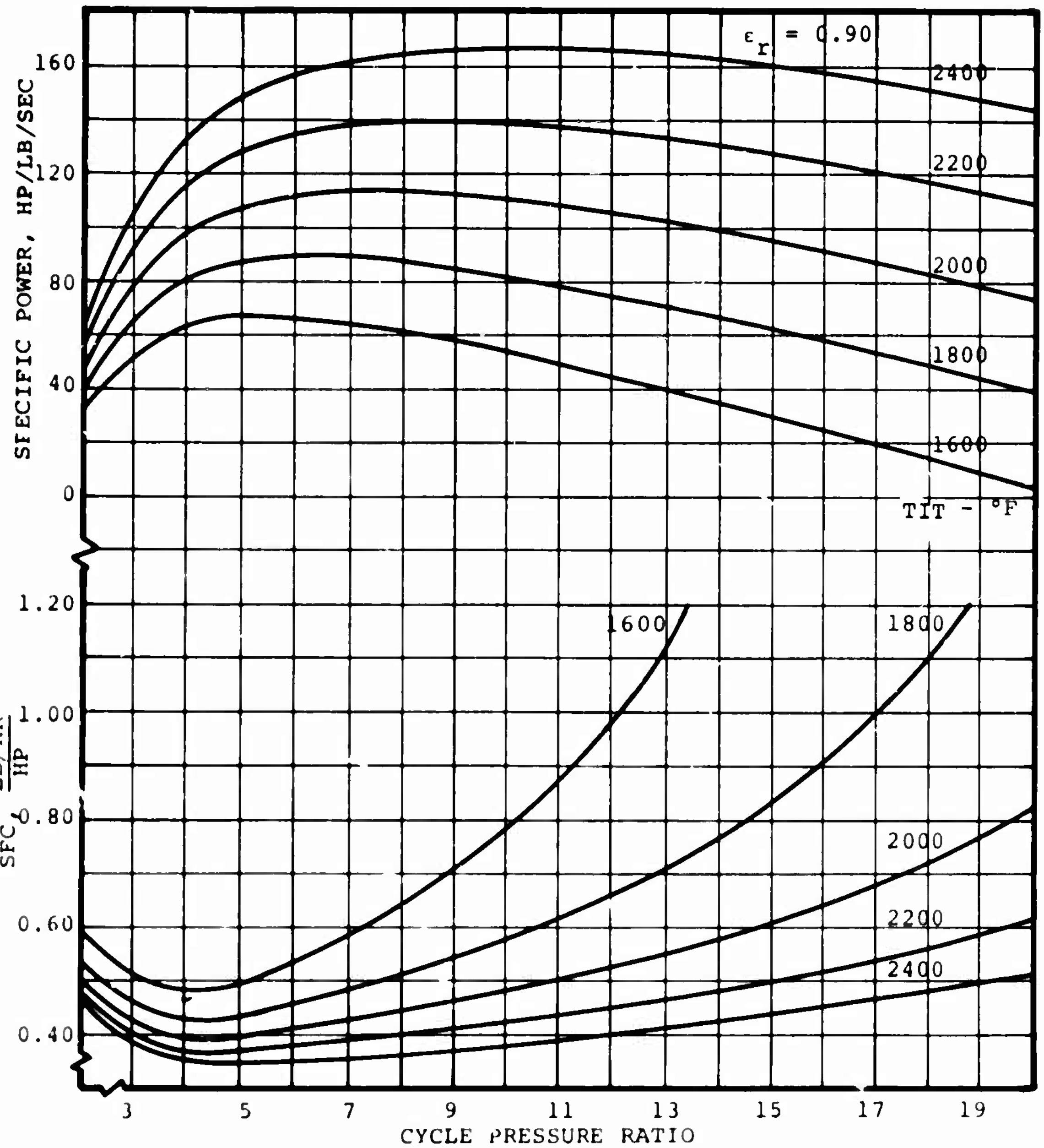


Figure 63. SFC and Specific Horsepower vs Cycle P/P, Regenerative, Technology Level III.

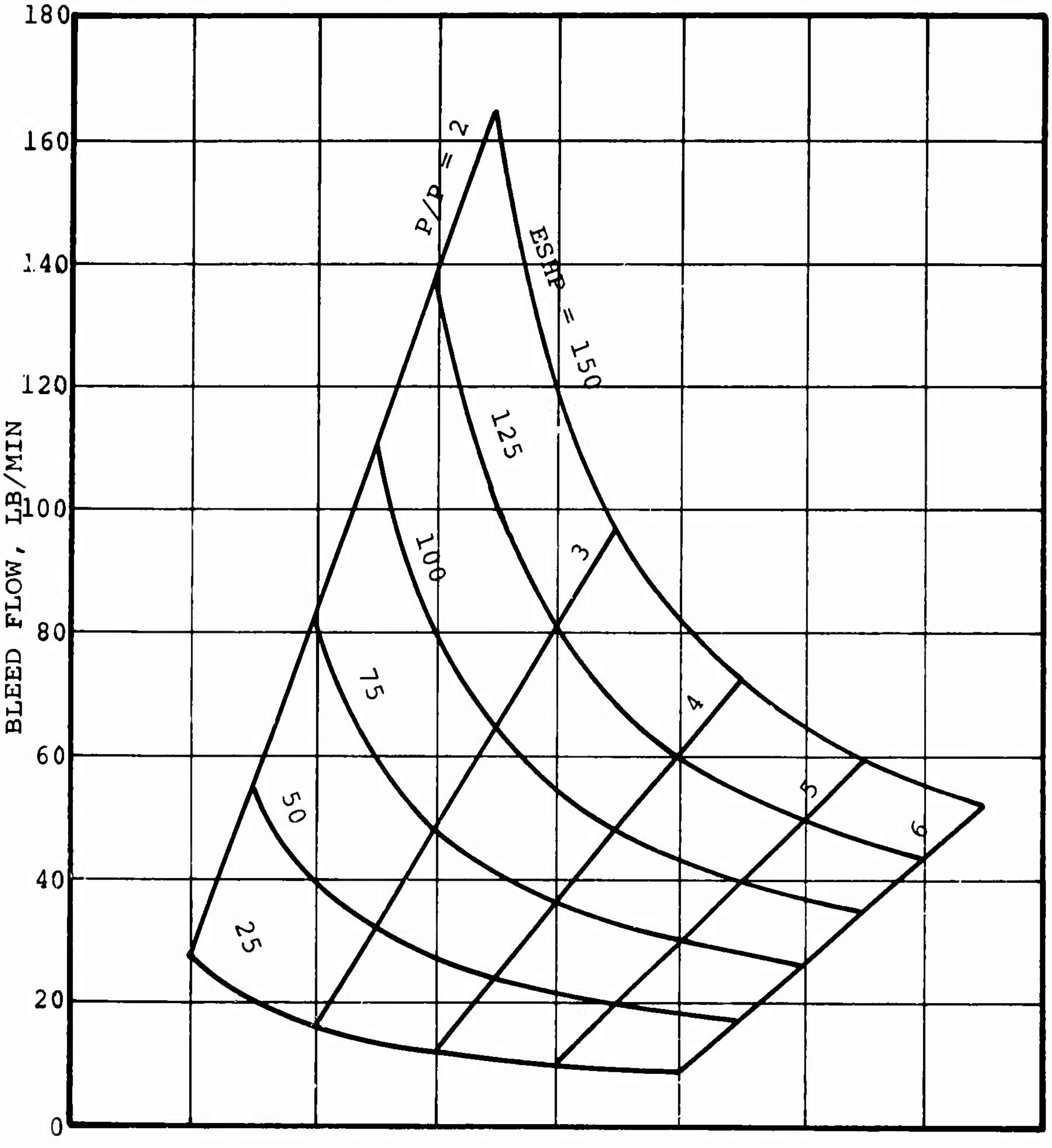


Figure 64. SHP Conversion to Bleed Flow vs P/P, Technology Level I.

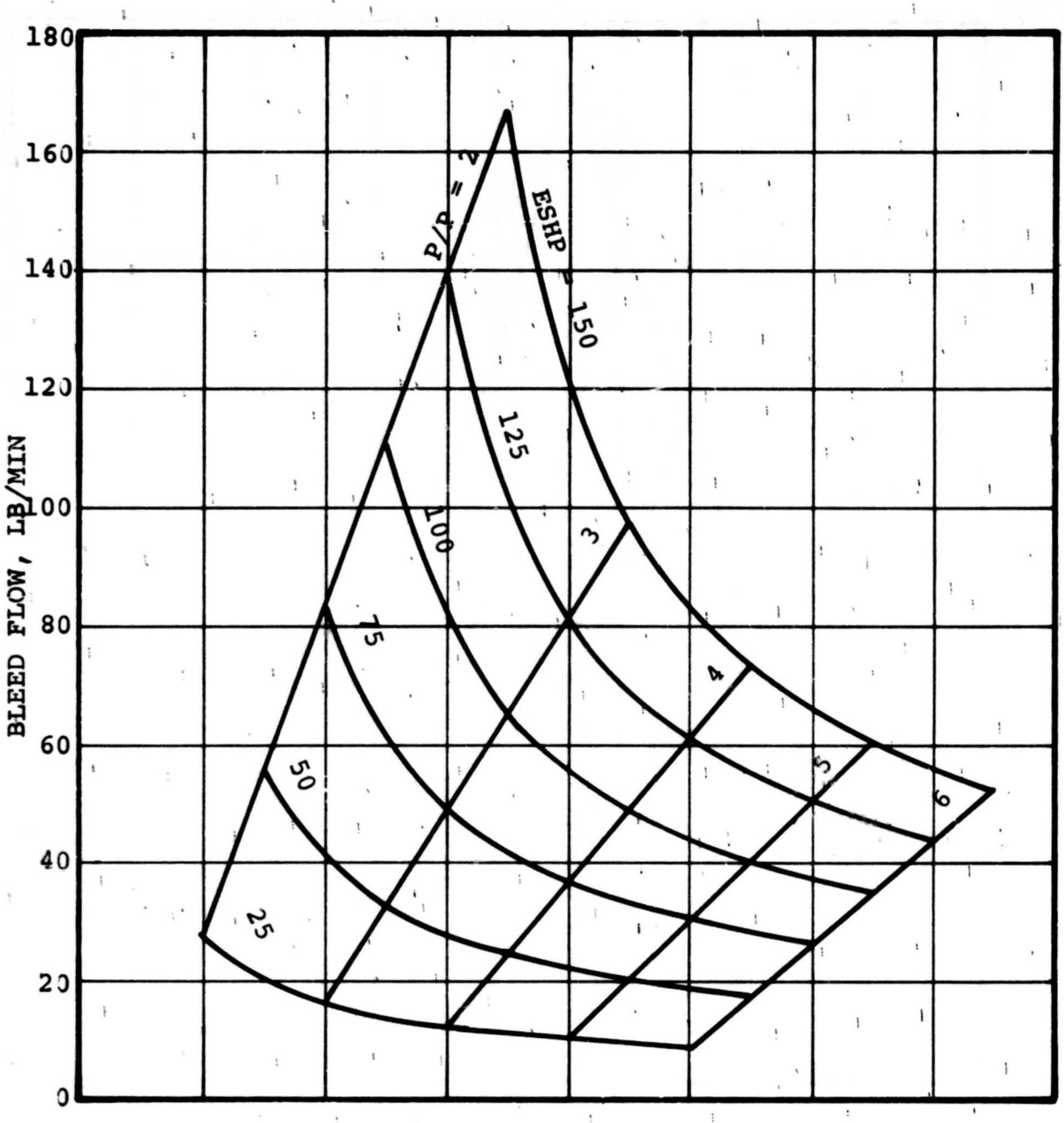


Figure 65. SHP Conversion to Bleed Flow vs P/P, Technology Level II.

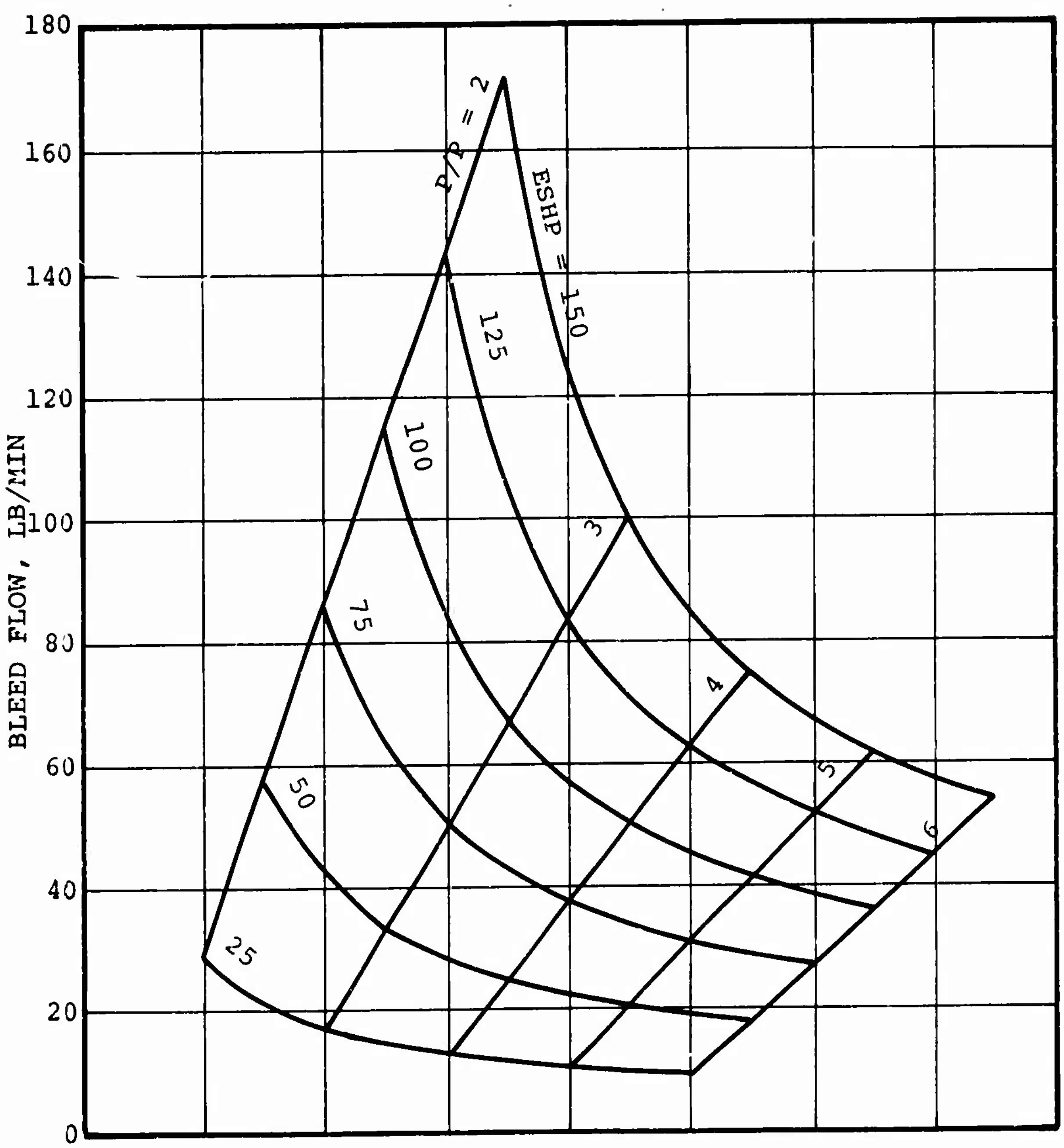


Figure 66. SHP Conversion to Bleed Flow vs P/P, Technology Level III.

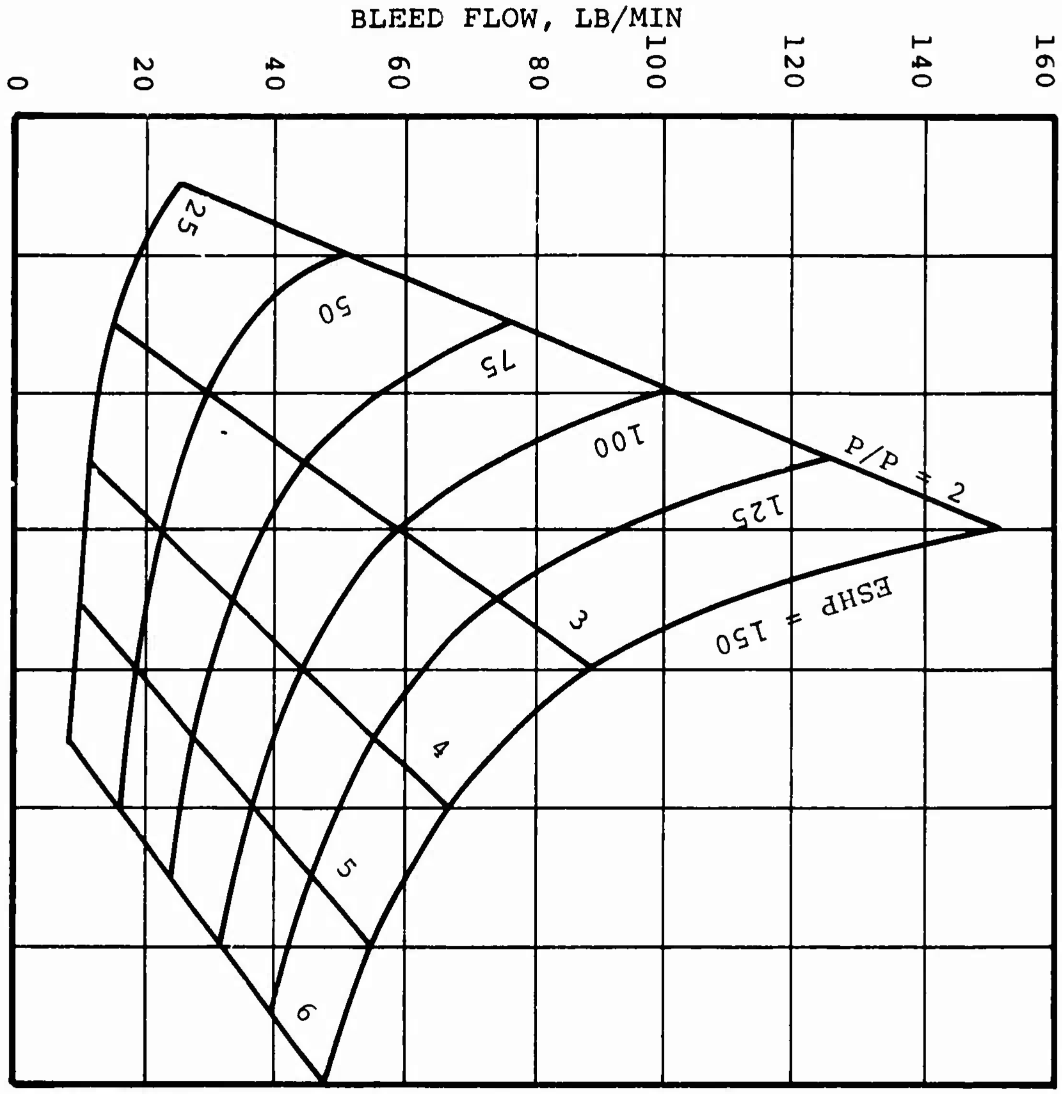


Figure 67. Shaft Horsepower Conversion to Bleed Flow vs P/P, Notched Impeller, Technology Level I.

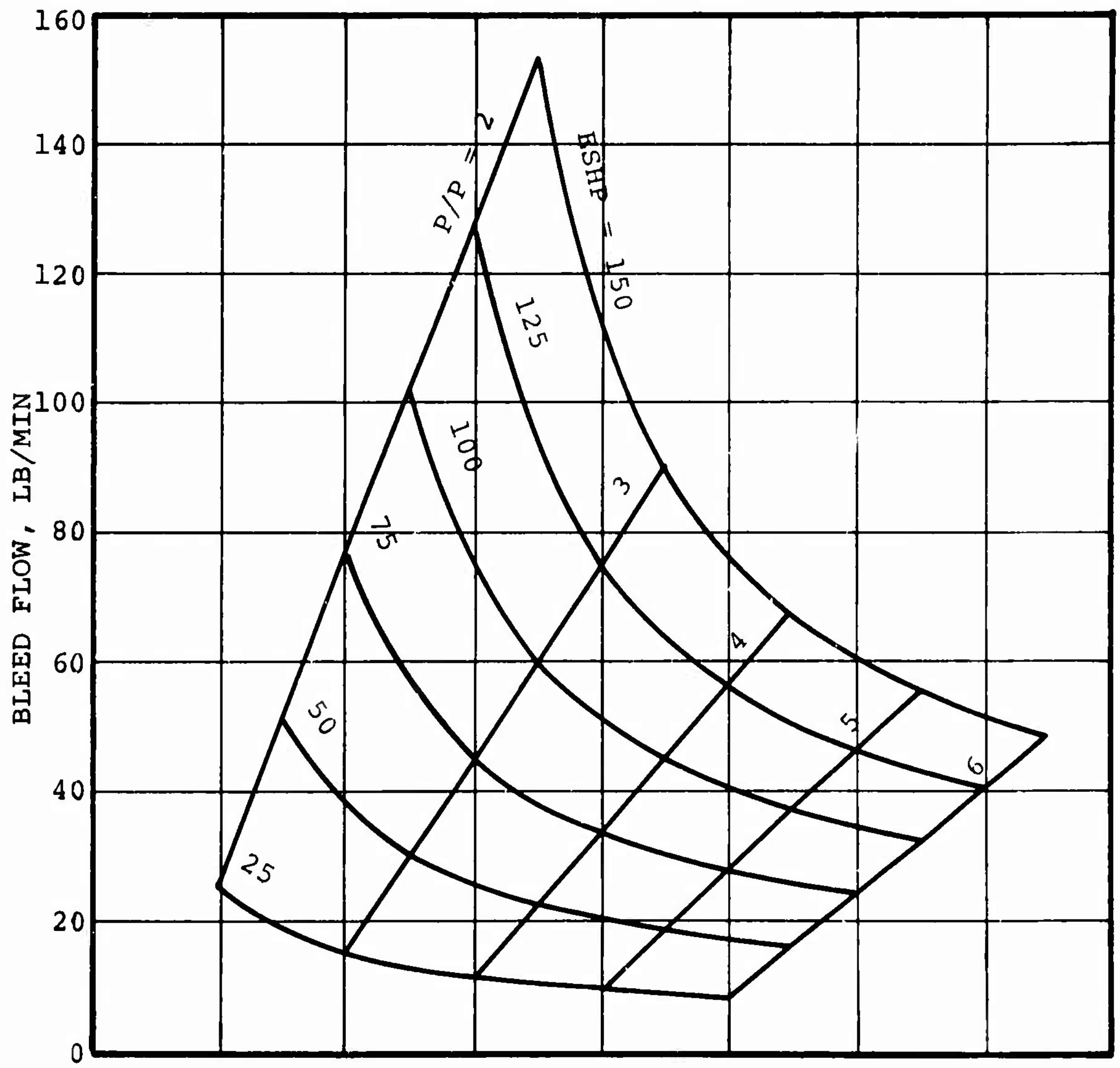


Figure 68. Shaft Horsepower Conversion to Bleed Flow vs P/P, Notched Impeller, Technology Level II.

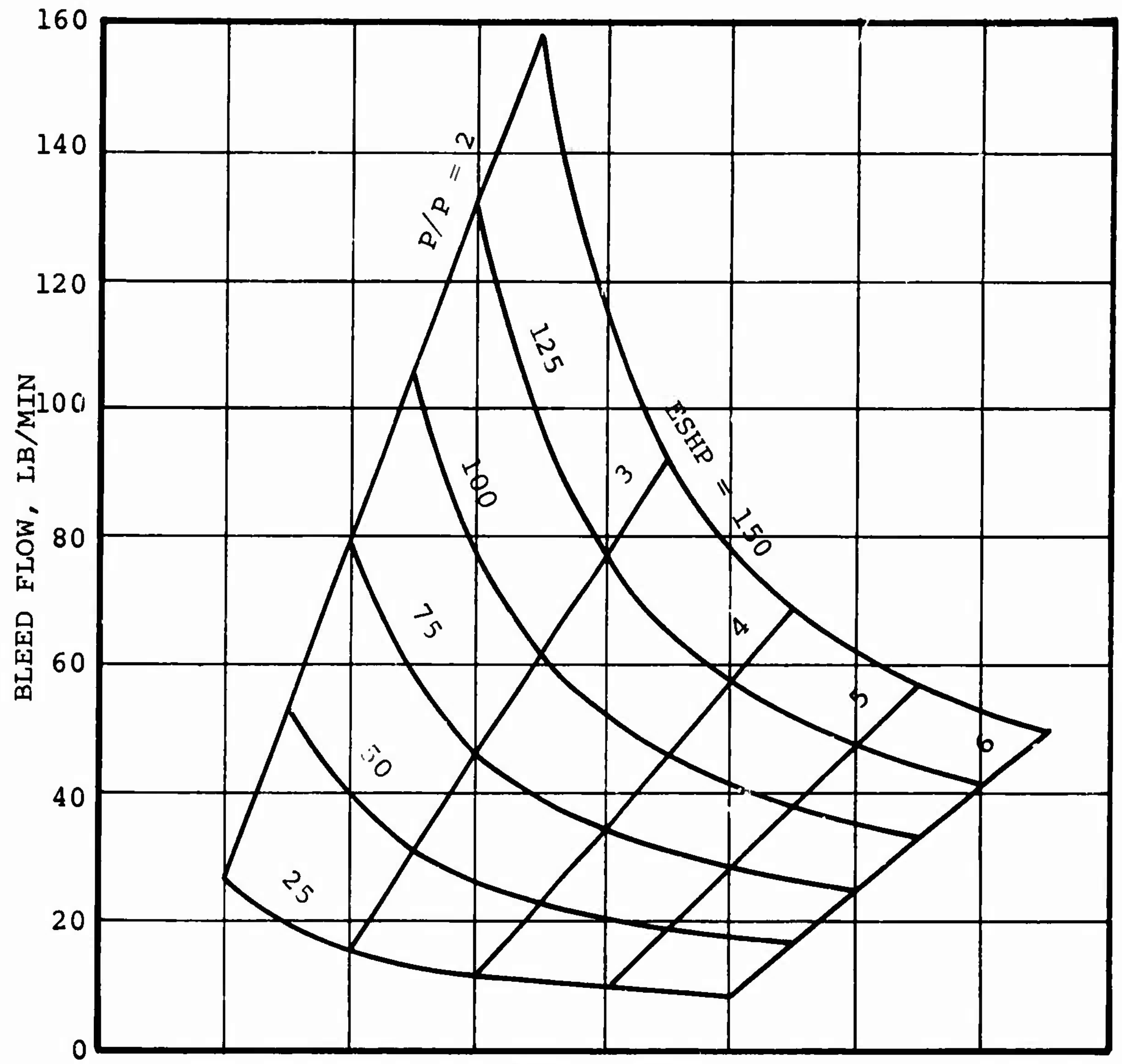


Figure 69. Shaft Horsepower Conversion to Bleed Flow vs P/P, Notched Impeller, Technology Level III.

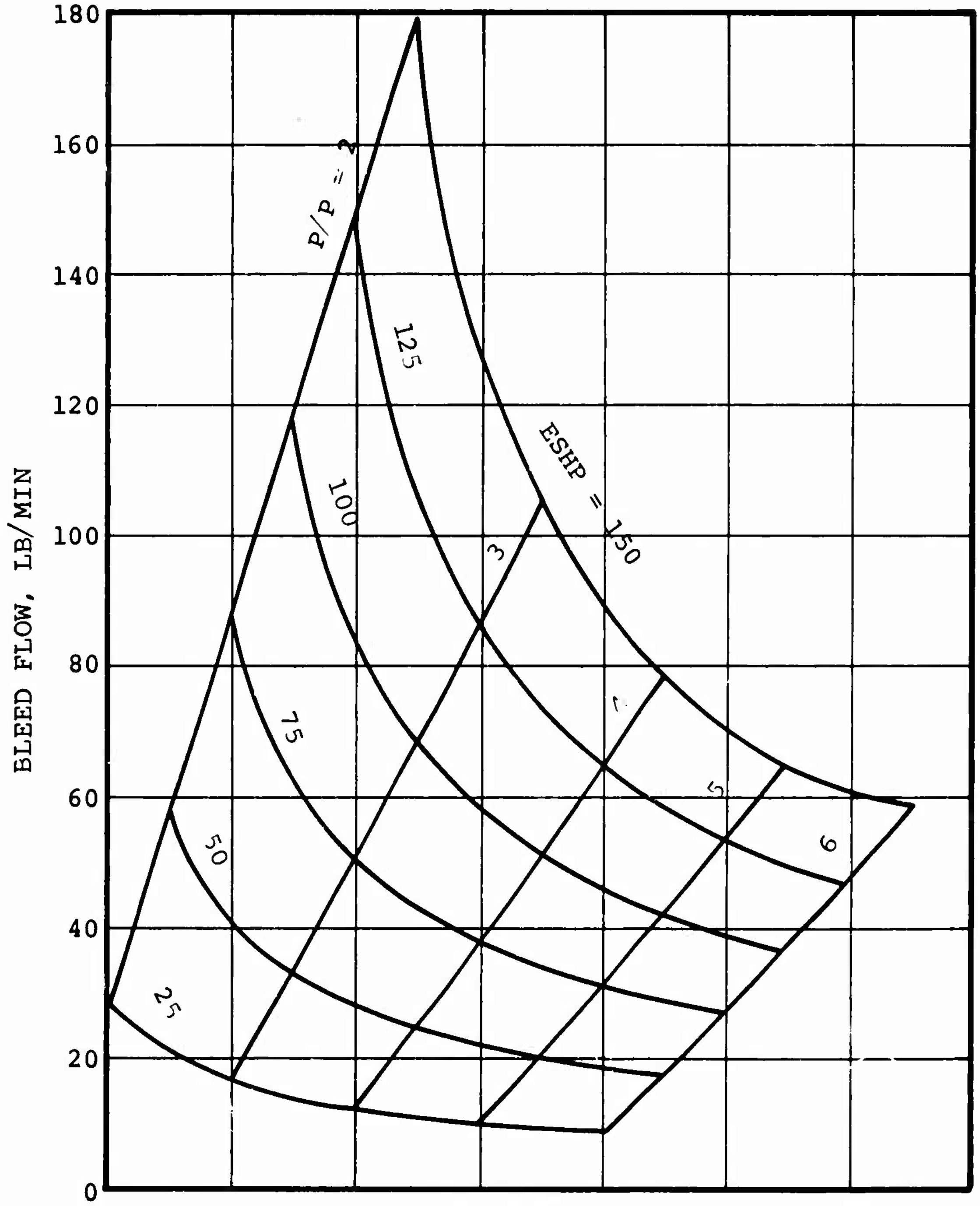


Figure 70. SHP Conversion to Bleed Flow, Load Compressor, Technology Level I.

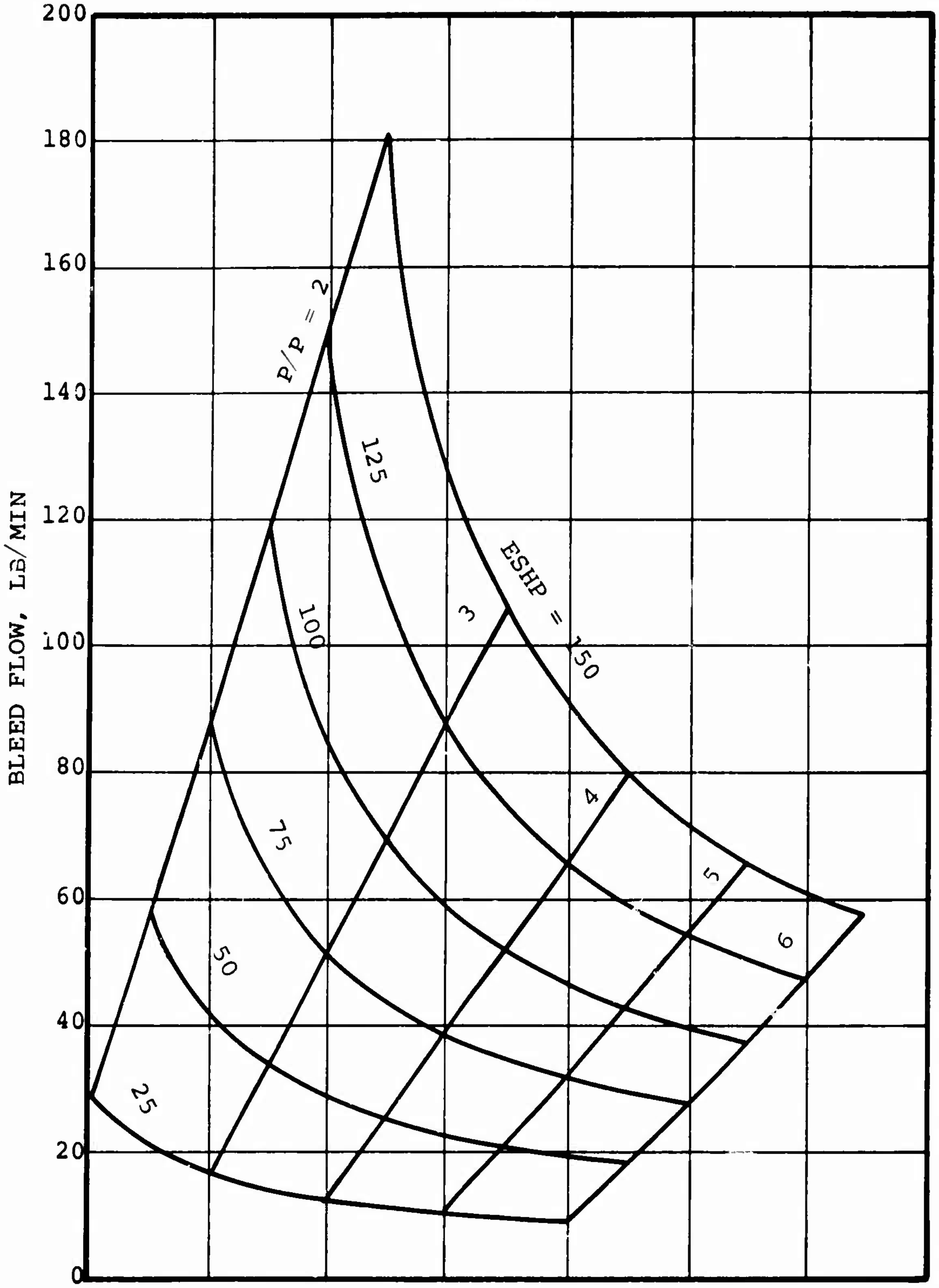


Figure 71. SHP Conversion to Bleed Flow, Load Compressor, Technology Level II.

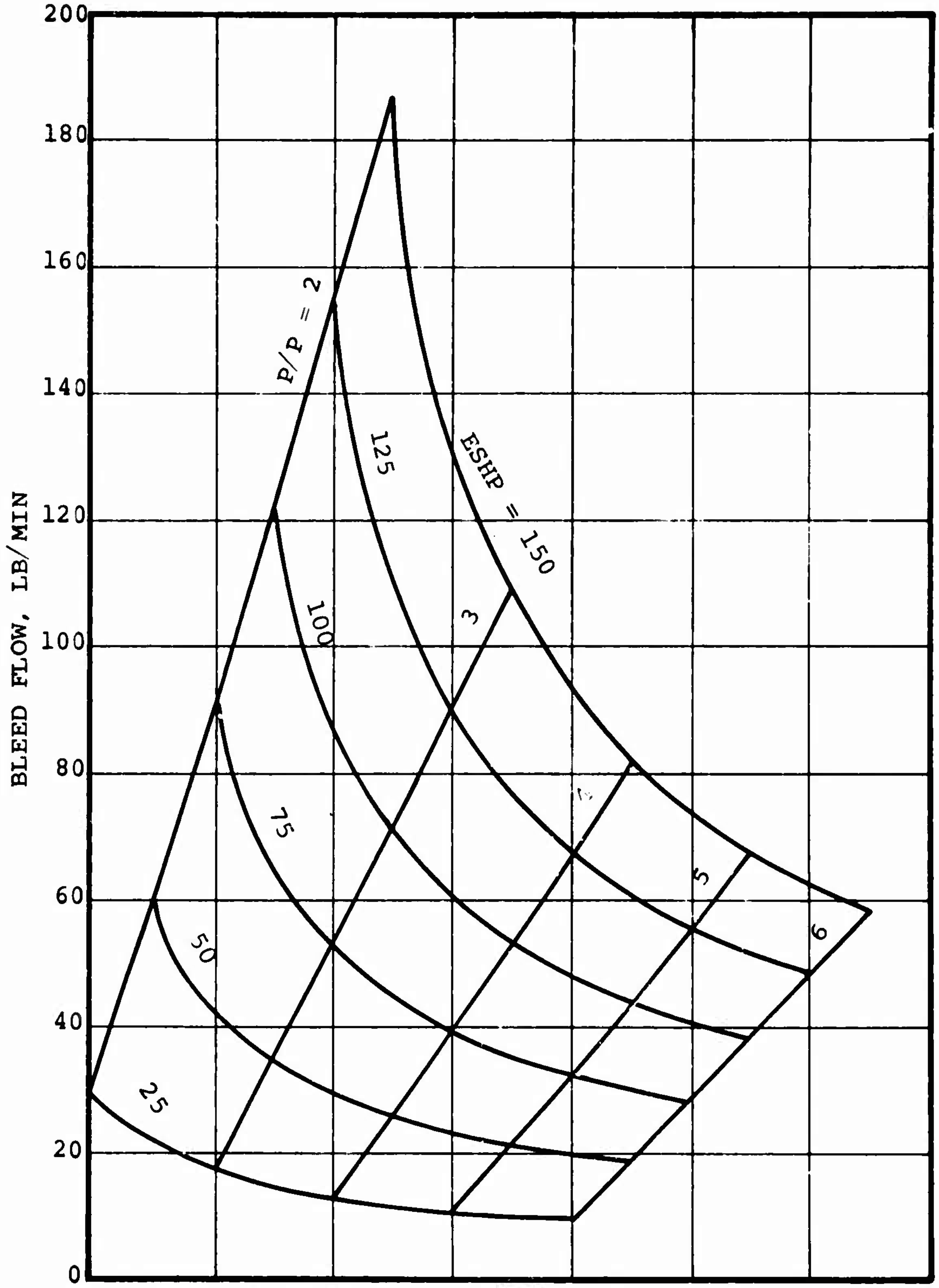


Figure 72. SHP Conversion to Bleed Flow, Load Compressor, Technology Level III.

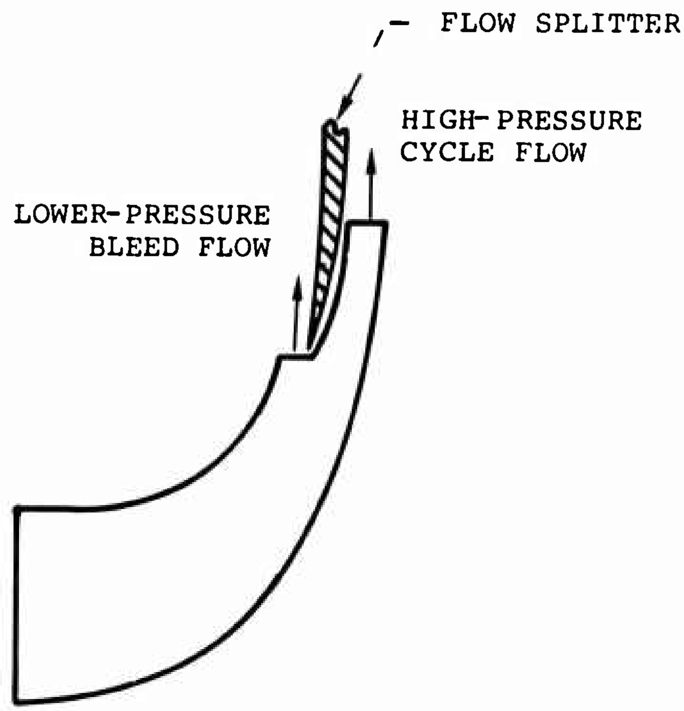


Figure 73. Notched Impeller Schematic.

The addition of variable geometry (either compressor or turbine) to an APU configuration that furnishes both shaft and bleed power can improve off-design performance over that shown in Figure 74. However, this performance improvement is achieved at the expense of reliability, maintainability, complexity, etc.

Figures 75 through 80 summarize the comparative non-regenerated APU configuration/cycle analysis which takes into account cycle parameters, performance, reliability, etc. A schematic of the APU configuration and a component description for the three technology periods are included in each figure. Cost, mechanical, and performance comparisons are also included.

Final Cycle and Configuration Selection

The final candidates, selected as a result of the APU parametric study, include the non-regenerated and regenerated cycles. The following parameters were narrowed to a recommended range for each technology level:

1. Turbine inlet temperature
2. Overall cycle pressure ratio

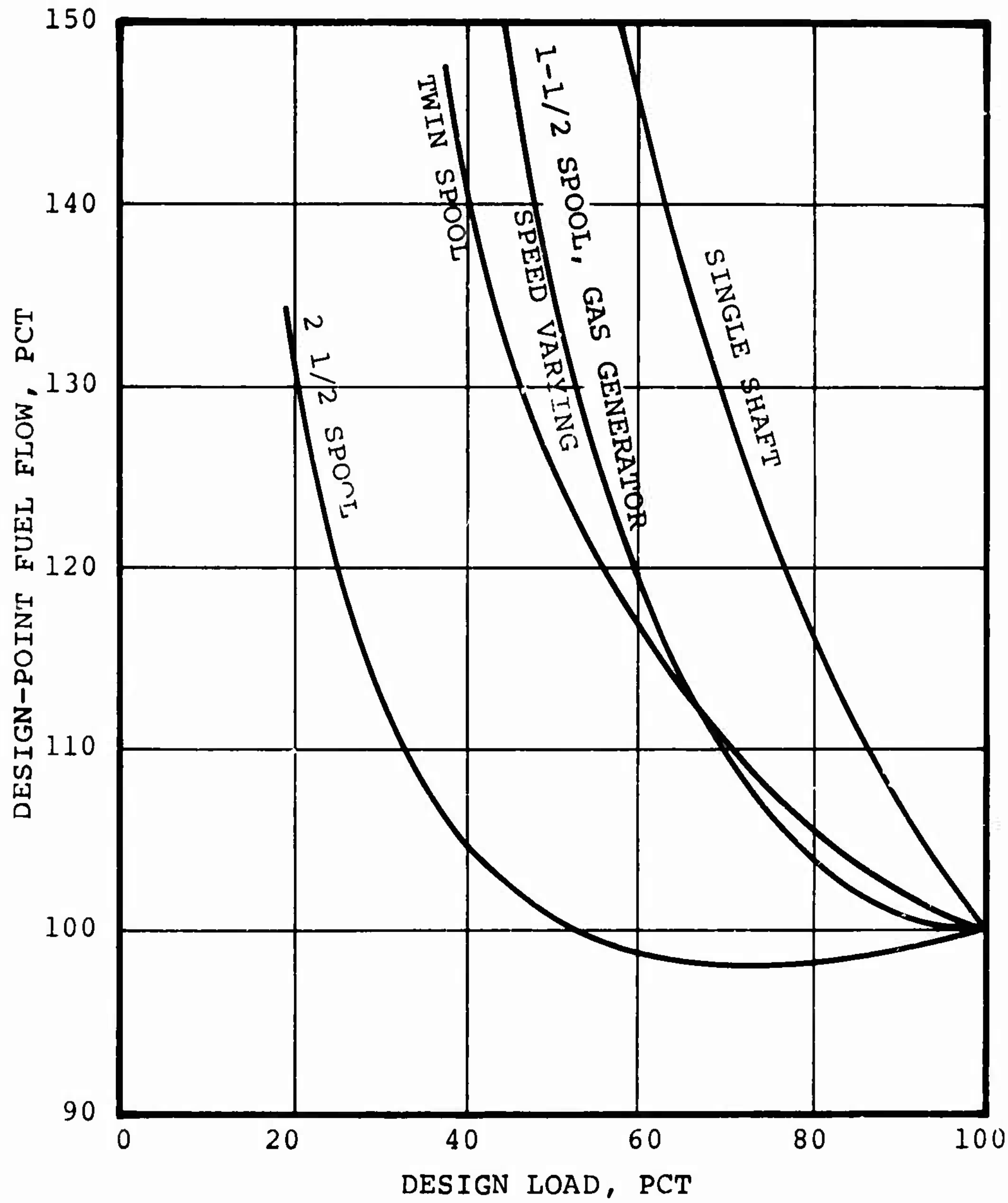


Figure 74. Relative Off-Design Cycle Performance Comparison.

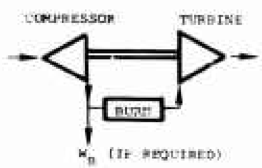
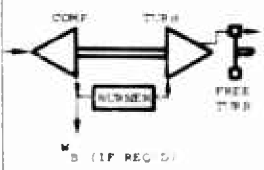
SINGLE SHAFT/NONREGEN 	T I M E	APU COMPONENT DESCRIPTION (POSSIBILITIES)	DESIGN-POINT AND OFF-DESIGN CONSIDERATION	1 MAINTAINABILITY 2 RELIABILITY 3 COMPLEXITY 4 VULNERABILITY	1 INITIAL LIFE CYCLE COST 2 INITIAL MANUFACTURING COST
CONFIGURATION DESCRIPTION • SINGLE SHAFT DESIGN • COMPRESSOR CONFIGURATIONS MAY BE RADIAL, AXIAL OR AXIAL/RADIAL • INTEGRAL BLEED, OR SHAFT POWER WITH OR WITHOUT LOAD COMPRESSOR • TURBINE CONFIGURATION DEPENDENT ON CYCLE PRESSURE RATIO BECAUSE THE HIGH CYCLE PRESSURE RATIOS GENERALLY REQUIRE MULTIPLE STAGE TURBINE ARRANGEMENTS • MULTIPLE COMPRESSOR STAGES ALLOW DIFFERENT BLEED PRESSURES • ROLLING ELEMENT ANTI-FRICTION BEARINGS FOR 1970 TECHNOLOGY • FOIL GAS BEARINGS FOR 1975 TECHNOLOGY • PIVOTED PAD OR FOIL GAS BEARINGS FOR 1985 TECHNOLOGY • NONREGENERATED CONFIGURATIONS WILL HAVE HIGH EXHAUST TEMPERATURES AND ARE SUSCEPTIBLE TO IR DETECTION	1970	• SINGLE-STAGE RADIAL COMPRESSOR P/P UP TO 6:1 • MULTIPLE-STAGE AXIAL COMPRESSOR P/P UP TO 4:1 • AXIAL/RADIAL COMPRESSOR P/P UP TO 8:1 WITH VARIABLE GEOMETRY/POSSIBLE NOTCHED IMP. • SINGLE-STAGE RADIAL TURBINE FOR P/P ≤6 • RADIAL/AXIAL TURB OR ALL AXIAL STAGES FOR P/P >6 • COOLING REQ'D FOR TIT >1800°F • SMALL TURB. SIZE HARD TO COOL BEYOND 2000°F • CONVENTIONAL COMBUSTOR <2000°F	• SINGLE-SHAFT ENGINES GENERALLY EXHIBIT POOR OFF-DESIGN PERFORMANCE • ADDITION OF VARIABLE GEOMETRY IN COMPRESSOR AND TURBINE AREAS HELPS CONSIDERABLY • MECHANICAL TURBINE VARIABLE GEOMETRY PRESENTS DESIGN PROBLEMS FOR SMALL TURBOMACHINERY • REQUIRES HIGH CYCLE P/P AND TIT FOR LOW SFC AT DESIGN POINT	1• SINGLE-SHAFT CONFIGURATION HAS BEST MAINTAINABILITY IF WITHOUT VARIABLE GEOMETRY 2• LOW NUMBER OF SIMPLE PARTS RESULTS IN HIGHLY RELIABLE APU's 3• WITHOUT VARIABLE GEOMETRY, SINGLE-SHAFT APU's ARE SIMPLEST GAS TURBINE DESIGN 4• SINGLE SHAFT APU's ARE SMALLER THAN OTHER CYCLES CONFIG'S AND, THEREFORE, HAVE SMALLEST SILHOUETTE	1 • SINGLE-SHAFT CONFIGURATION HAS FEWER COMPLEX PARTS AND LONGER TBO's • ADDITION OF VARIABLE GEOMETRY REDUCES TBO AND INCREASES PROCUREMENT COST • FUEL CONSUMPTION HIGH WITHOUT VARIABLE GEOMETRY 2 • SIMPLE COMPONENTS HAVE LOWEST COST OF MANUFACTURE FOR SINGLE-SHAFT CONFIGURATION
	1975	• SINGLE-STAGE RADIAL COMPRESSOR P/P UP TO 10:1 • MULTIPLE-STAGE AXIAL COMPRESSOR P/P UP TO 6:1 • AXIAL/RADIAL COMPRESSOR P/P UP TO 11:1 WITH VARIABLE GEOMETRY POSSIBLE NOTCHED IMPELLER • SINGLE-STAGE RADIAL FOR P/P <10 • COOLING REQUIRED FOR TIT 1800°F • CERAMIC COATED COMBUSTORS • MULTIPLE TURBINE STAGES REQ'D FOR P/P >10	• VARIABLE GEOMETRY DESIGN PROBLEMS REDUCED • OFF-DESIGN PERFORMANCE COMPARABLE TO MULTIPLE SPOOL GAS TURBINES IF VARIABLE GEOMETRY IS UTILIZED IN COMPRESSOR AND TURBINE AREAS • POSSIBLE USE OF JET FLAP OR BOUNDARY LAYER CONTROL • REQUIRES HIGH CYCLE P/P AND TIT FOR LOW SFC AT DESIGN POINT	• IMPROVEMENTS IN MANUFACTURING, MATERIALS, DESIGN, AND CONTROLS WILL ALLOW THE USE OF VARIABLE GEOMETRY IN SINGLE-SHAFT APU's WITH SIGNIFICANTLY SMALLER PENALTIES IN COMPLEXITY, MAINTAINABILITY, AND RELIABILITY • APU SILHOUETTE DOES NOT CHANGE SIGNIFICANTLY WITH ADDITION OF VARIABLE GEOMETRY	• TECHNOLOGY ADVANCES WILL REDUCE MANUFACTURING COSTS FOR BASIC COMPONENTS AND VARIABLE GEOMETRY • MATERIAL IMPROVEMENTS AND ADDITION OF JOURNAL BEARINGS WILL IMPROVE TBO • VARIABLE GEOMETRY WILL REDUCE FUEL CONSUMPTION
	1985	• SINGLE-STAGE RADIAL COMPRESSOR P/P UP TO 14:1 • MULTIPLE STAGE AXIAL COMP. P/P UP TO 8:1 • AXIAL/RADIAL COMPRESSOR P/P UP TO 16:1 WITH VARIABLE GEOMETRY POSSIBLE NOTCHED IMPELLER • RADIAL TURBINE FOR P/P <14 • TWO STAGE TURBINE FOR P/P >14 • POSSIBLE AERODYNAMICALLY VARIABLE COMPRESSOR AND TURBINE GEOMETRY • UNCOOLED TURBINES AND COMBUSTORS UP TO 2400°F	• DEVELOPMENT OF AERODYNAMICALLY VARIABLE GEOMETRY ALLOWS IMPROVED OFF-DESIGN PERFORMANCE WITHOUT WEIGHT, COMPLEXITY, ETC. OF MECHANICALLY VARIABLE GEOMETRY • REQUIRES HIGH CYCLE P/P AND TIT FOR LOW SFC AT DESIGN POINT	• AERODYNAMICALLY VARIABLE GEOMETRY REDUCES MAINTAINABILITY, RELIABILITY, AND COMPLEXITY PENALTIES CONSIDERABLY AND MAKES THE APU COMPARABLE TO ONE WITHOUT VARIABLE GEOMETRY • APU SILHOUETTE SAME FOR NO VARIABLE GEOMETRY AND AERODYNAMIC VARIABLE GEOMETRY	• IMPROVED OFF-DESIGN PERFORMANCE BY USE OF AERODYNAMIC VARIABLE GEOMETRY • COST OF AERODYNAMIC VARIABLE GEOMETRY LOW COMPARED TO MECHANICALLY VARIABLE GEOMETRY • INCREASED TBO WITH AERODYNAMICALLY VARIABLE GEOMETRY • MANUFACTURING TECHNOLOGY ADVANCES AND AERODYNAMICALLY VARIABLE GEOMETRY WILL REDUCE INITIAL PRODUCTION COSTS • GAS BEARINGS EXTEND TBO

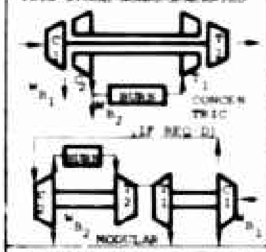
Figure 75. Single-Shaft APU Analysis.

FREE-TURBINE (NONREGENERATED)	TIME	APU COMPONENT DESCRIPTION (POSSIBILITIES)	DESIGN-POINT AND OFF-DESIGN CONSIDERATION	1 MAINTAINABILITY 2 RELIABILITY 3 COMPLEXITY 4 VULNERABILITY	1 INITIAL LIFE CYCLE COST 2 INITIAL MANUFACTURING COST
 CONFIGURATION DESCRIPTION ● 1-1/2 SPOOL FREE-TURBINE ● CONCENTRIC POWER SHAFT OR REAR POWER DRIVE ● INTEGRAL BLEED* OR LOAD COMPRESSOR IF BLEED IS REQUIRED ● BEARING TECHNOLOGY SAME AS IN FIG. 75 ● MULTIPLE COMPRESSOR STAGES POSSIBLE WHICH WILL ALLOW DIFFERENT BLEED P/P ● MULTIPLE TURBINE STAGES REQUIRED FOR MULTIPLE COMPRESSOR STAGES AT HIGH CYCLE P/P	1970	● PRESSURE RATIO RANGE SAME AS FIG. 75 FOR COMPRESSORS ● LOW CYCLE PRESSURE RATIO WILL ALLOW USE OF SINGLE-STAGE GAS GENERATOR TURBINE ● RADIAL GAS GENERATOR TURBINE FOR HIGHER CYCLE P/P ● TURBINE INLET TEMPERATURE CONSIDERATIONS SAME AS FIG. 75 ● COMBUSTOR CONSIDERATIONS SAME AS FIG. 75 ● VARIABLE COMPRESSOR OR TURBINE GEOMETRY POSSIBLE ● MODULAR CONSTRUCTION POSSIBLE WITH REAR POWER DRIVE	● OFF-DESIGN PERFORMANCE OF CONSTANT SPEED (GAS GEN AND FREE TURB) IS COMPARABLE WITH SINGLE-SHAFT ENGINE ● ALLOWING GAS GENERATOR SPEED TO FLOAT IMPROVES OFF-DESIGN PERFORMANCE ● VARIABLE TURBINE GEOMETRY YIELDS FURTHER IMPROVEMENT ● REQUIRES HIGH CYCLE P/P AND TIT FOR LOW SFC AT DESIGN POINT	1 MAINTAINABILITY NOT AS GOOD AS SINGLE-SHAFT CONFIGURATION DUE TO LARGER NUMBER OF PARTS 2 RELIABILITY DECREASED FOR SAME REASON 3 COMPLEXITY OF FREE-TURBINE TO BE CONSIDERED 4 INCREASED SIZE RESULTS IN LARGER SILHOUETTE ESPECIALLY FOR MODULAR CONSTRUCTION (EASIER MAINTENANCE)	1 ● INITIAL PROCUREMENT COST HIGHER THAN SINGLE-SHAFT DUE TO GREATER COMPLEXITY OF FREE-TURBINE ● ADDITION OF VARIABLE GEOMETRY INCREASES COST AND REDUCES FUEL FLOW AT OFF-DESIGN POINTS BUT TBO WILL BE DECREASED BY ADDITIONAL COMPLEXITY 2 ● INITIAL MANUFACTURING COST WILL BE GREATER DUE TO MORE COMPONENTS THAN SINGLE-SHAFT
	1975	● COMPRESSOR P/P SAME AS FIG. 75 ● WITH INCREASED RADIAL TURBINE CAPABILITY, CYCLE P/P CAN BE INCREASED W/O USING MULTIPLE GAS GENERATOR TURBINE STAGES ● TURBINE INLET TEMPERATURE CONSIDERATIONS SAME AS FIG. 75 ● COMBUSTOR CONSIDERATIONS SAME AS FIG. 75 ● MECHANICALLY VARIABLE COMP/TURB GEOMETRY ● MODULAR CONSTRUCTION POSSIBLE WITH REAR DRIVE BUT IS LARGER THAN CONCENTRIC DRIVE	● USE OF VARIABLE TURBINE GEOMETRY RESULTS IN GREATLY IMPROVED OFF-DESIGN PERFORMANCE ● REQUIRES HIGH CYCLE P/P AND TIT FOR LOW SFC AT DESIGN POINTS ● POSSIBLE LOCK-UP DEVICE TO ENABLE FREE-TURBINE TO FEED POWER INTO GAS GENERATOR WHICH WILL IMPROVE OFF-DESIGN PERFORMANCE	● USE OF VARIABLE GEOMETRY IN BOTH 1970 AND 1975 WILL DECREASE RELIABILITY AND MAINTAINABILITY WHILE INCREASING COMPLEXITY ● POSSIBLE USE OF CONCENTRIC DESIGN TO REDUCE APU SILHOUETTE ● MODULAR CONSTRUCTION FOR EASIER MAINTENANCE POSSIBLE	● SAME AS FIG. 75 EXCEPT THAT FREE-TURBINE CONFIGURATION WILL STILL HAVE HIGHER INITIAL COST THAN SINGLE-SHAFT AND OFF-DESIGN PERFORMANCE WILL BE IMPROVED (UNLESS SINGLE-SHAFT REQUIRES VARIABLE GEOMETRY)
	1985	● COMPRESSOR P/P SAME AS FIG. 75 ● RADIAL TURBINE FOR GAS GENERATOR WILL ALLOW CYCLE P/P OF 20:1 ● TURBINE INLET TEMPERATURE CONSIDERATIONS SAME AS FIG. 75 ● AERODYNAMICALLY VARIABLE TURB/COMP GEOMETRY ● COMBUSTOR CONFIGURATION SAME AS FIG. 75 ● MODULAR CONSTRUCTION POSSIBLE	● SAME AS FIG. 75	● SAME AS FIG. 75 ● MODULAR CONSTRUCTION FOR EASY MAINTENANCE	● SAME AS FIG. 75 EXCEPT THAT FREE-TURBINE CONFIGURATION WILL STILL HAVE HIGHER INITIAL COST THAN SINGLE-SHAFT AND OFF-DESI[illegible] PERFORMANCE WILL BE [illegible]OVED (UNLESS SINGLE-SHAFT REQUIRES VARIABLE GEOMETRY)

*LOCKUP FREE TURBINE IF LOAD SCHEDULE REQUIRES

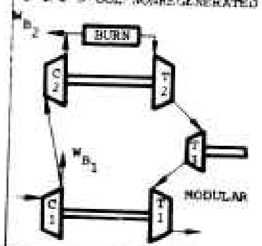
Figure 76. Free-Turbine APU Analysis.

TWIN-SPOOL NONREGENERATED



CONFIGURATION DESCRIPTION	TIME	APU COMPONENT DESCRIPTION (POSSIBILITIES)	DESIGN-POINT AND OFF-DESIGN CONSIDERATION	1 MAINTAINABILITY 2 RELIABILITY 3 COMPLEXITY 4 VULNERABILITY	1 INITIAL LIFE CYCLE COST 2 INITIAL MANUFACTURING COST
• T'N N SPOOL CONFIGURATION • EITHER CONCENTRIC OR MODULAR CONSTRUCTION • TWIN COMPRESSORS ALLOW FOR EASY EXTRACTION OF BLEED AT DIFFERENT PRESSURE LEVELS • POSSIBLE USE OF NOTCHED IMPELLER OR LOAD COMPRESSOR IF REQUIRED • SHAFT POWER EXTRACTION FROM EITHER SHAFT POSSIBLE • COMPRESSOR CONFIGURATION LIMITED TO MULTIPLE STAGE AXIAL OR SINGLE STAGE ..DIAL PER SHAFT • BEARING ..CHNOLOGY SAME AS IN FIG. ..	19[illegible]0	• COMPRESSOR AND TURBINE PRESSURE RATIO RANGES SAME AS FIG. 75 • TURBINE I'.. TEMP/COOLING AND COMBUSTOR CO'..URATION SAME AS FIG. 75 • MECHANICALLY VARIABLE GEOMETRY FOR TURBINES AND COMPRESSORS	• OFF-DESIGN PERFORMANCE WITHOUT VARIABLE GEOMETRY IS BETTER THAN SINGLE-SHAFT OR FREE-TURBINE WITHOUT VARIABLE GEOMETRY • VARIABLE GEOMETRY IMPROVES OFF-DESIGN PERFORMANCE • VARIABLE SPEED ON ONE SHAFT ALSO IMPROVES OFF-DESIGN PERFORMANCE IF DUTY CYCLE REQUIRES • REQUIRES HIGH CYCLE P/P AND TIT FOR LOW SFC AT DESIGN POINT	1 • CONCENTRIC CONFIG HAS POORER MAINTAINABILITY THAN FREE-TURBINE OR SINGLE-SHAFT • MODULAR CONSTRUCTION REDUCES MAINTAINABILITY PROBLEM 2 • RELIABILITY DECREASED DUE TO INCREASED NUMBER OF PARTS 3 • COMPLEXITY INCREASED DUE TO INCREASED NUMBER OF PARTS 4 • CONCENTRIC CONFIG SILHOUETTE COMPARABLE TO SINGLE-SHAFT APU BUT MODULAR CONSTRUCTION DOUBLES SILHOUETTE	1 • GREATER COMPLEXITY WILL RESULT IN HIGHER INITIAL COST THAN FREE-TURBINE OR SINGLE-SHAFT • BETTER FUEL CONSUMPTION CAN BE REALIZED BY VARIABLE GEOMETRY BUT COMPLEXITY INCREASES AND TWO WILL BE DECREASED 2 • TWIN-SPOOL CONFIGURATION WILL BE MORE DIFFICULT TO PRODUCE AND WILL THEREFORE HAVE A HIGHER INITIAL MANUFACTURING COST
	1975	• SAME AS ABOVE	• SAME AS ABOVE	• SAME AS FIG. 75 BUT INCREASES MAINTAINABILITY	• SAME AS FIG. 75
	19[illegible]5	• COMPRESSOR AND TURBINE PRESSURE RATIO RANGES SAME AS FIG. 75 • TURBINE INLET TEMP/COOLING AND COMBUSTOR CONFIGURATION SAME AS FIG. 75 • POSSIBLE AERODYNAMICALLY VARIABLE GEOMETRY	• SAME AS ABOVE EXCEPT FOR USING AERODYNAMICALLY VARIABLE GEOMETRY	• SAME AS FIG. 75	• SAME AS FIG. 75

Figure 77. Twin-Spool APU Analysis.



2-1-2 SPOOL NONREGENERATED	TIME	APU COMPONENT DESCRIPTION (POSSIBILITIES)	DESIGN-POINT AND OFF-DESIGN CONSIDERATION	1 MAINTAINABILITY 2 RELIABILITY 3 COMPLEXITY 4 VULNERABILITY	1 INITIAL LIFE CYCLE COST 2 INITIAL MANUFACTURING COST
CONFIGURATION DESCRIPTION ● TWO-AND-ONE-HALF SPOOL DESIGN ● MODULAR CONSTRUCTION OR CONCENTRIC DESIGN POSSIBLE ● POWER TURBINE LOCATED FOR 3:1 STALL TORQUE RATIO ● BEARING TECHNOLOGY SAME AS FIG. 66 ● TWIN COMPRESSORS ALLOW EASY EXTRACTION OF BLEED AT DIFFERENT PRESSURE LEVELS ● POSSIBLE USE OF NOTCHED IMPELLER OR LOAD COMPRESSOR IF REQUIRED ● COMPRESSOR CONFIGURATION LIMITED TO MULTIPLE-STAGE AXIAL OR SINGLE-STAGE RADIAL PER SHAFT	1970	● SAME AS FIG. 77	● 2-1/2 SPOOL DESIGN HAS EXCELLENT OFF-DESIGN PERFORMANCE WITHOUT VARIABLE GEOMETRY ● ADDITION OF VARIABLE TURBINE GEOMETRY GIVES BEST OFF-DESIGN PERFORMANCE ● REQUIRES HIGH CYCLE P/P AND TIT FOR LOW SFC AT DESIGN-POINT	● MAINTAINABILITY, RELIABILITY AND COMPLEXITY DO NOT COMPARE FAVORABLY WITH PREVIOUS CONFIGURATIONS DUE TO GREATER NUMBER OF PARTS AND STRUCTURE INVOLVED ● VULNERABILITY FOR MODULAR CONSTRUCTION IS HIGH, DUE TO LARGE SILHOUETTE - CONCENTRIC DESIGN HELPS TO LOWER VULNERABILITY	1 ● IMPROVED OFF-DESIGN PERFORMANCE OFFSET BY HIGH INITIAL COST, DUE TO COMPLEXITY ● TBO REDUCED, DUE TO COMPLEXITY 2 ● TWO-AND-ONE-HALF SPOOL APU WILL BE MORE DIFFICULT TO PRODUCE THAN PREVIOUS CONFIGURATIONS AND WILL HAVE HIGHER INITIAL MANUFACTURING COST
	1975	● SAME AS FIG. 77	● SAME AS ABOVE	● SAME AS ABOVE	● SAME AS ABOVE EXCEPT THAT USE OF JOURNAL BEARINGS WILL INCREASE TBO
	1985	● SAME AS FIG. 77	● SAME AS ABOVE EXCEPT FOR AERODYNAMICALLY VARIABLE GEOMETRY	● SAME AS ABOVE EXCEPT THAT USE OF AERODYNAMICALLY VARIABLE GEOMETRY REDUCES COMPLEXITY AND MAINTAINABILITY WHILE INCREASING RELIABILITY	● SAME AS ABOVE EXCEPT THAT USE OF GAS BEARINGS AND AERODYNAMICALLY VARIABLE GEOMETRY WILL REDUCE COMPLEXITY, IMPROVE MAINTAINABILITY AND RELIABILITY, AND INCREASE TBO

Figure 78. Two-and-One-Half Spool APU Analysis.

ALL CONFIGURATIONS/REGEN	TIME	APU COMPONENT DESCRIPTION (POSSIBILITIES)	DESIGN-POINT AND OFF-DESIGN CONSIDERATION	1 MAINTAINABILITY 2 RELIABILITY 3 COMPLEXITY 4 VULNERABILITY	1 INITIAL LIFE CYCLE COST 2 INITIAL MANUFACTURING COST
● THE SCHEMATICS OF ALL THE REGENERATED CONFIGURATIONS WILL BE SIMILAR TO THE NONREGENERATED SCHEMATICS EXCEPT FOR THE ADDITION OF EITHER A FIXED BOUNDARY RECUPERATOR OR A ROTARY REGENERATOR BETWEEN THE COMPRESSOR DISCHARGE AND THE COMBUSTOR INLET	1970	● REGENERATED CYCLE COMPONENT DESCRIPTION SAME AS NON-REGENERATED FOR THE THREE TIME PERIODS EXCEPT FOR HEAT EXCHANGER ● HEAT EXCHANGER CONFIGURATIONS LIMITED TO FIXED-BOUNDARY RECUPERATORS ● CYCLE PRESSURE RATIOS LIMITED BY RECUPERATOR CONSTRUCTION ● RECUPERATOR EFFECTIVENESS TO 0.8	● OFF-DESIGN PERFORMANCE CHARACTERISTIC AS SHOWN IN FIG. 65 WILL IMPROVE SLIGHTLY OVER NON-REGENERATED CYCLES ● LOWER DESIGN-POINT SFC RESULTS IN SIGNIFICANTLY LOWER FUEL FLOWS AT OFF-DESIGN AND DESIGN CONDITIONS ● DESIGN-POINT CAN BE AT LOWER CYCLE P/P AND TIT AND STILL RETAIN-LOW SFC, WHICH ALLOWS USE OF LESS COMPLEX, MORE MAINTAINABLE COMPONENTS	1 MAINTAINABILITY OF A REGENERATED APU IS DECREASED BY ADDITION OF HEAT EXCHANGER 2 RELIABILITY IS DECREASED BY HEAT EXCHANGER, BUT LOWER TURBINE INLET TEMP POSSIBLE WHICH MAY OFFSET THIS 3 COMPLEXITY INCREASED BY HEAT EXCHANGER 4 VULNERABILITY IS INCREASED BY LARGER SILHOUETTE BUT DECREASED BY LOWER EXHAUST TEMPERATURE	1 ● FUEL CONSUMPTION WILL BE SUBSTANTIALLY REDUCED COMPARED TO NON-REGENERATED CYCLE ● TBO WILL BE REDUCED BY HEAT EXCHANGER ● INITIAL PROCUREMENT COST WILL BE HIGHER THAN NONREGENERATED CYCLE 2 ● MANUFACTURE OF METAL RECUPERATOR COSTLY AND RAISES INITIAL PROCUREMENT COST
CONFIGURATION DESCRIPTION ● PREVIOUS CONFIGURATION DESCRIPTIONS FOR THE NON-REGENERATED CYCLES ARE APPLICABLE TO THE REGENERATED CYCLE CONFIGURATIONS ● REGENERATION BY EITHER ROTARY REGENERATOR OR BY FIXED-BOUNDARY RECUPERATORS (DEPENDENT ON TIME PERIOD)	1975	● HEAT EXCHANGER CONFIGURATION EITHER FIXED-BOUNDARY RECUPERATOR OR ROTARY REGENERATOR ● POSSIBLE USE OF CERAMICS IN HEAT EXCHANGER CORES ● CERCOR ROTARY REGENERATORS ● CERVIT ROTARY REGENERATORS AND CROSS-FLOW FIXED BOUNDARY RECUPERATORS (CERAMIC) ● HEAT EXCHANGER EFFECTIVENESS TO 0.85 ● IMPROVEMENTS IN SEALS AND CONSTRUCTION WILL REDUCE LEAKAGE	● SAME AS ABOVE ● OVERALL PERFORMANCE IMPROVED BY LEAKAGE REDUCTION AND EFFECTIVENESS INCREASES	● DEVELOPMENT OF CERAMIC HEAT EXCHANGERS WILL INCREASE RELIABILITY AND MAINTAINABILITY OF REGENERATED CYCLES ● VULNERABILITY WILL BE DECREASED BY IMPROVED FABRICATION TECHNIQUES WHICH WILL DECREASE CORE SIZE AND PROVIDE BETTER PACKAGING	● SAME AS ABOVE EXCEPT FOR IMPROVEMENTS RESULTING FROM CERAMIC HEAT EXCHANGER DEVELOPMENT WHICH WILL REDUCE INITIAL PROCUREMENT AND MANUFACTURING COST AND INCREASE RELIABILITY
	1985	● SAME AS ABOVE EXCEPT FOR EFFECTIVENESS ● REGENERATOR EFFECTIVENESS TO 0.9	● SAME AS ABOVE	● SAME AS ABOVE	● SAME AS ABOVE

Figure 79. Regeneration Analysis for All Cycles.

ALL CONFIGURATIONS/AFTER-HEAT	TIME	APU COMPONENT DESCRIPTION (POSSIBILITIES)	DESIGN-POINT AND OFF-DESIGN CONSIDERATION	1 MAINTAINABILITY 2 RELIABILITY 3 COMPLEXITY 4 VULNERABILITY	1 INITIAL LIFE CYCLE COST 2 INITIAL MANUFACTURING COST
• THE SCHEMATICS OF THE AFTER-HEAT CONFIGURATIONS WILL BE SIMILAR TO THE NONREGENERATED SCHEMATICS EXCEPT FOR THE ADDITION OF A ROTARY REGENERATOR BETWEEN THE TURBINE INLET AND THE COMBUSTOR DISCHARGE AND THE RELOCATION OF THE COMBUSTOR BEHIND THE TURBINE	1970	• BEYOND SCOPE OF 1970 HEAT EXCHANGER TECHNOLOGY			
CONFIGURATION DESCRIPTION • PREVIOUS CONFIGURATION DESCRIPTIONS FOR NON-REGENERATED CYCLES ARE APPLICABLE TO AFTER-HEAT CYCLE CONFIGURATIONS • REGENERATION BY ROTARY REGENERATOR	1975	• CERAMIC ROTARY REGENERATOR CAPABLE OF TAKING HIGH COMBUSTOR DISCHARGE TEMPERATURE • REGENERATOR EFFECTIVENESS TO 0.85 • REQUIRES LARGE COMBUSTOR FOR NEARLY ATMOSPHERIC PRESSURE COMBUSTION	• SAME AS FIG. 79 EXCEPT FOR SLIGHTLY HIGHER DESIGN-POINT SFC	• SAME AS FIG. 79 EXCEPT FOR FOLLOWING • MAINTAINABILITY AND RELIABILITY INCREASED BY USE OF "CLEAN AIR" IN TURBINE SECTION • VULNERABILITY INCREASED BY LARGE SILHOUETTE CAUSED BY LARGE COMBUSTOR AND HIGHER EXHAUST TEMP	• SAME AS FIG. 79 EXCEPT THAT TBO WILL BE EXTENDED BY USE OF CLEAN AIR IN TURBINE SECTION
	1985	• SAME AS ABOVE EXCEPT FOR REGENERATOR EFFECTIVENESS TO 0.[illegible]	• SAME AS ABOVE	• SAME AS ABOVE	• SAME AS ABOVE

Figure 80. After-Heat Analysis for All Cycles.

3. Bleed air pressure

4. Maximum heat exchanger effectiveness

The component efficiencies, etc., from Tables XXV through XXXIII corresponding to the selected parameters were used.

The basis of selection included consideration of:

1. Performance

   (a) Design-point

   (b) Off-design

2. Practical Considerations

   (a) Initial manufacturing cost

   (b) Maintainability

   (c) Reliability

   (d) Complexity

   (e) Vulnerability

   (f) Life-cycle cost

   (g) Size

   (h) Weight

The goals of good performance and improved maintainability, reliability, etc., were the major criteria.

The after-heat cycle was eliminated on the basis of size and weight. Figure 81 shows a curve of corrected flow ratio into the combustor as a function of turbine inlet temperature for a cycle at Technology Level II. The combustor corrected flow for the after-heat cycle is over five times that for the regenerated cycle. Therefore, the combustor size for the after-heat cycle would be significantly larger than that of the regenerated or non-regenerated. This, with the requirement for high values of regenerator effectiveness to obtain a low SFC, results in a large, heavy APU. The size and weight penalties associated with this cycle would offset any advantage for this application.

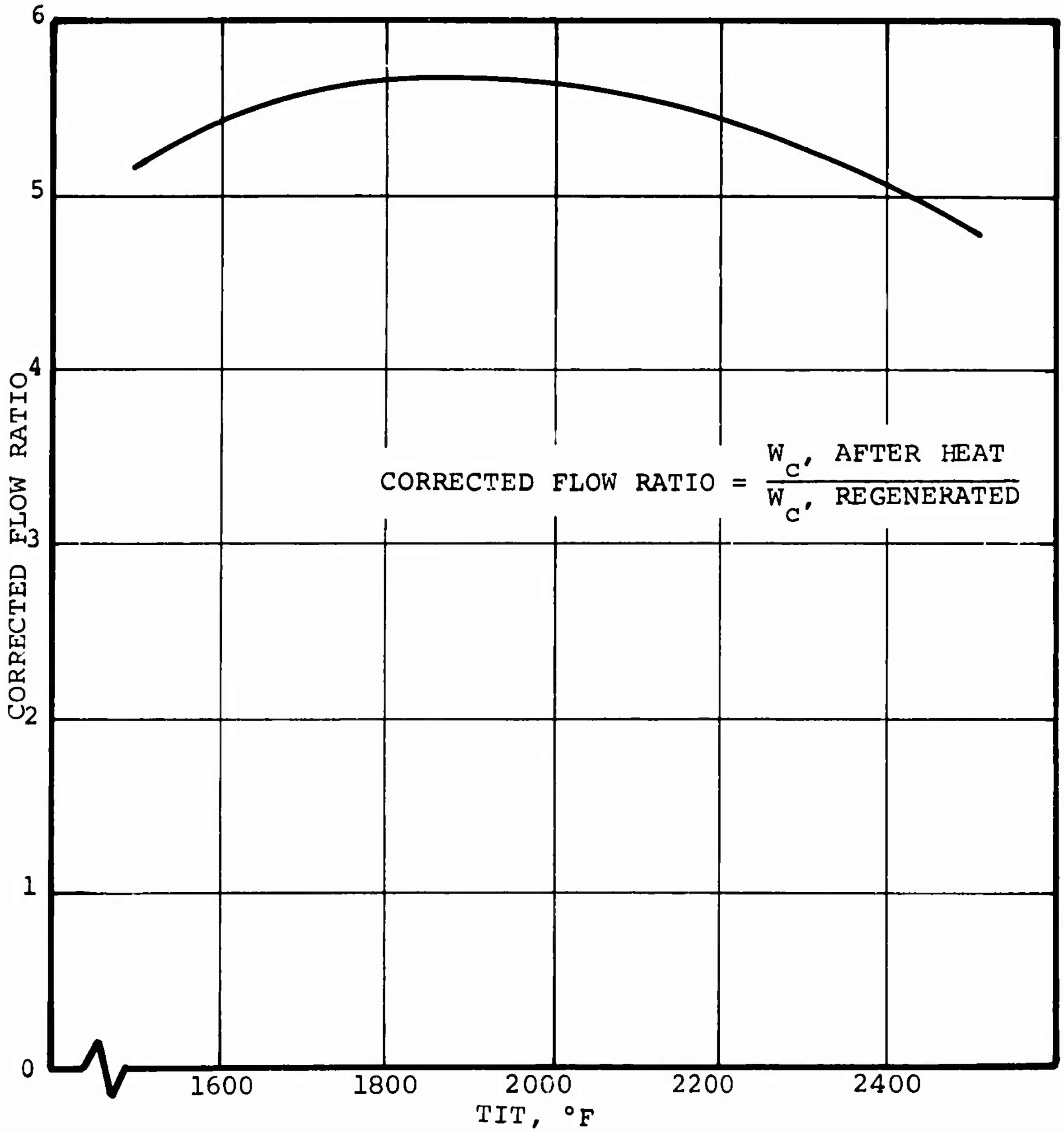


Figure 81. Comparison of After-Heat and Regenerated Cycle Corrected Flows Into Combustor for Technology Level II.

The regenerated and the non-regenerated cycles were selected for further analysis. Table XXXIV summarizes these cycles and the parametric ranges to be considered. Consideration of in-power generation is the primary reason for retaining the regenerated cycle. If the APU is continuously used in flight, the fuel consumption will be critical. The low SFC's possible with the regenerated cycle will significantly reduce the fuel consumed for a given duty cycle. The regenerated cycle is analyzed in Subsection 8.4.3 for in-flight use.

The appropriate range for turbine inlet temperature and cycle pressure ratio was determined by a parametric analysis (Figures 58-72), in conjunction with the comparative analysis (Figures 75-80). Practical limits were placed on the turbine inlet temperature to avoid the manufacturing difficulties and complexities in small high-speed turbomachinery. Figures 58 through 63, show that the specific power (for a given pressure ratio) continuously increases as the turbine inlet temperature

TABLE XXXIV. RECOMMENDED CYCLE PARAMETER RANGES

Technology Level	TIT	P/P_{cycle}	P/P_{bleed}	ε_r*
I**	1780-1850	3 - 6	3 - 4	-
II**	1850-1950	4 - 7	4 - 5	-
III**	1950-2200	5 - 9	5 - 6	-
I+	1650-1750	3 - 5	3 - 4	0.80
II+	1750-1850	4 - 6	4 - 5	0.85
III+	1850-1950	5 - 7	5 - 6	0.90

*Values of regenerator effectiveness are practical limits for the technology periods. The actual values of ε_r will be optimized for the selected system.

**Nonregenerated APU.

+Regenerated APU.

increases. However, the SFC (for a given pressure ratio) does not decrease continuously as the turbine inlet temperature increases but actually starts leveling out. This, in conjunction with mechanical considerations, established the turbine inlet temperature ranges.

Cycle pressure ratios were selected to maximize the specific horsepower and minimize the SFC for the selected TIT ranges. Practical limits of pressure ratio imposed by small turbomachinery were again considered in the pressure ratio selection.

The SFC and specific horsepower curves (Figures 58-63) show that the optimum cycle pressure ratios occur at lower values for the regenerated cycles. Lower values of turbine inlet temperature were used because of the inherently low design-point SFC of the regenerated cycle. The lower TIT reduces the mechanical complexity of the APU without a significant SFC penalty.

The cycle/configuration analysis summarized in Figures 74 through 80 was used to select the optimum APU configuration for this application. The single-shaft configuration (integral bleed/shp or pure shaft power) without variable geometry was selected. While the 1-1/2, 2 and 2-1/2 spool configurations have better off-design performance characteristics than the single shaft (Figure 74), the additional complexity, size, weight, etc., of the multiple-spool engines offsets the performance advantages. For turbomachinery in this size, multiple-spool APUs requiring two or more compressor and turbine stages would be difficult to manufacture and would have a high initial cost. The simple, rugged construction of the single-shaft configuration is smaller than multiple-spool arrangements and has better maintainability and reliability characteristics.

Radial turbines and compressors were selected in lieu of axial components. Radial flow turbomachinery in this size is easier and cheaper to manufacture, is less sensitive to foreign object damage and dirt/dust ingestion, is less sensitive to clearances and tolerances than axial components, exhibits higher efficiencies, and is capable of higher pressure ratios in a single stage.

The notched impeller concept was eliminated, due to the possible erosion of the flow splitter (Figure 73) from dirt/dust ingestion associated with helicopter operation. This erosion would present a maintainability and reliability problem. The method of supplying bleed-air was limited to load compressor or conventional bleed/shaft power APU, where the bleed-air is taken at the APU cycle pressure ratio.

Figures 82, 83, and 84 are general layouts of the selected APU configurations for the three technology periods. These configurations were used in establishing weight and volume data in Section 6.7.3.

6.7.2 Performance Analysis

The APU design-point shaft and bleed power requirements for the 27 basic candidate systems are given on Table XXXV for SPS without ECS and on Table XXXVI for SPS with ECS. These power requirements are for a 130°F day and are listed for the various modes of APU operation for each technology level. The APU size is determined from the total maximum simultaneous power shown on Table VIII.

The fuel flow requirements for the bleed/shaft-power APU were calculated using the efficiencies and other cycle parameters in Subsection 6.7.1. The fuel flow requirements at the design-point for bleed/shaft APU are given for Technology Levels I, II, and III in Figures 85, 86, and 87, respectively, and for shaft-power-only APU in Figure 88.

Off-design fuel requirements were determined for an arbitrary APU size for 130°F sea-level conditions and normalized to obtain percent of design-point fuel flow as a function of percent of design-point equivalent horsepower. Similar data were generated to obtain the maximum continuous and off-design performance at altitudes to 30,000 ft and hot-day conditions. These data are plotted in Figure 89.

6.7.3 Sizing

Table XXXIV summarizes the recommended cycle parameter ranges of turbine inlet temperature, cycle pressure ratio, and bleed pressure ratio. The range is based on the maximum predicted parameters, with the higher values associated with the larger APU and the lower values with the smaller APU. These table values were derived from the curves in Figure 90, from which the cycle parameters are determined as functions of eshp (Table VIII).

Since the notched impeller concept was eliminated for the candidate bleed/shaft APU, the maximum bleed pressure ratio at the APU determines the minimum cycle pressure ratio. The bleed pressure ratios in the study are shown in Table XXXVII.

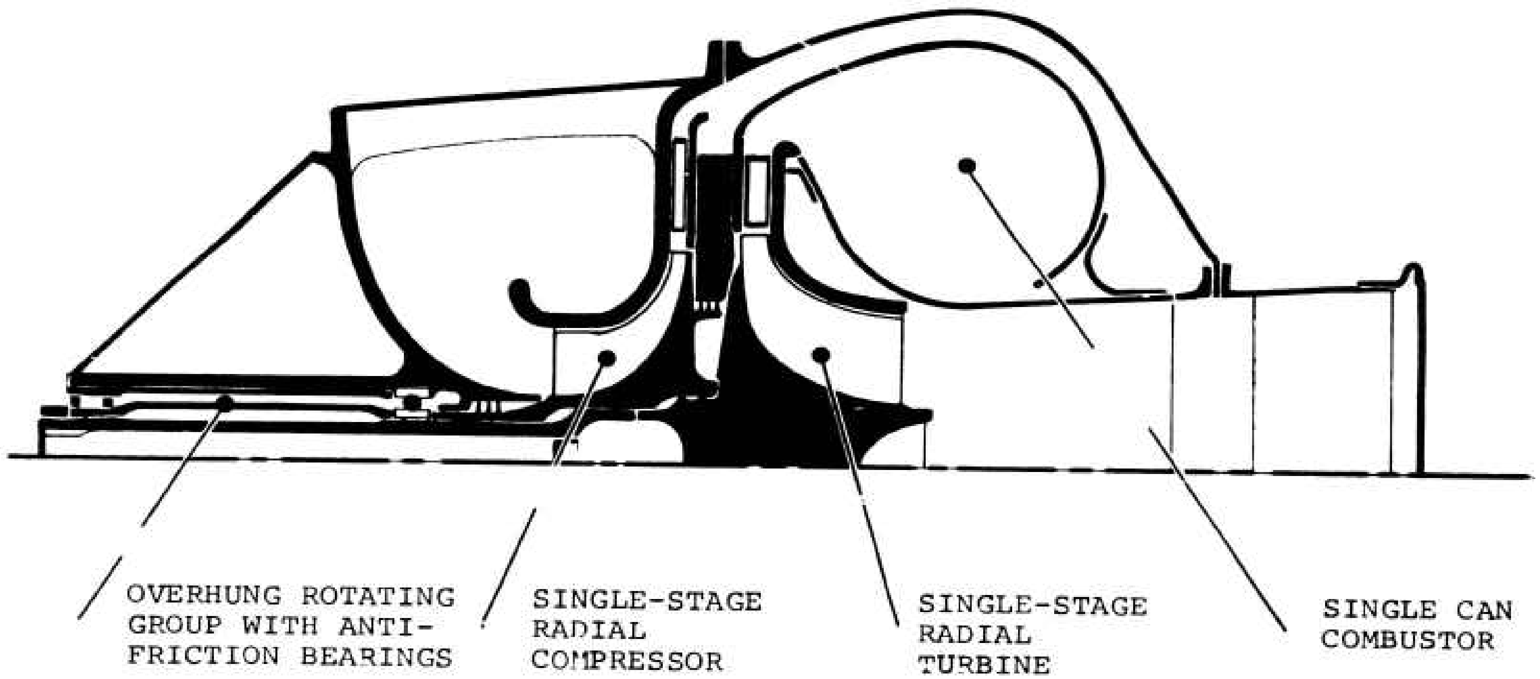


Figure 82. Technology Level I APU Configuration.

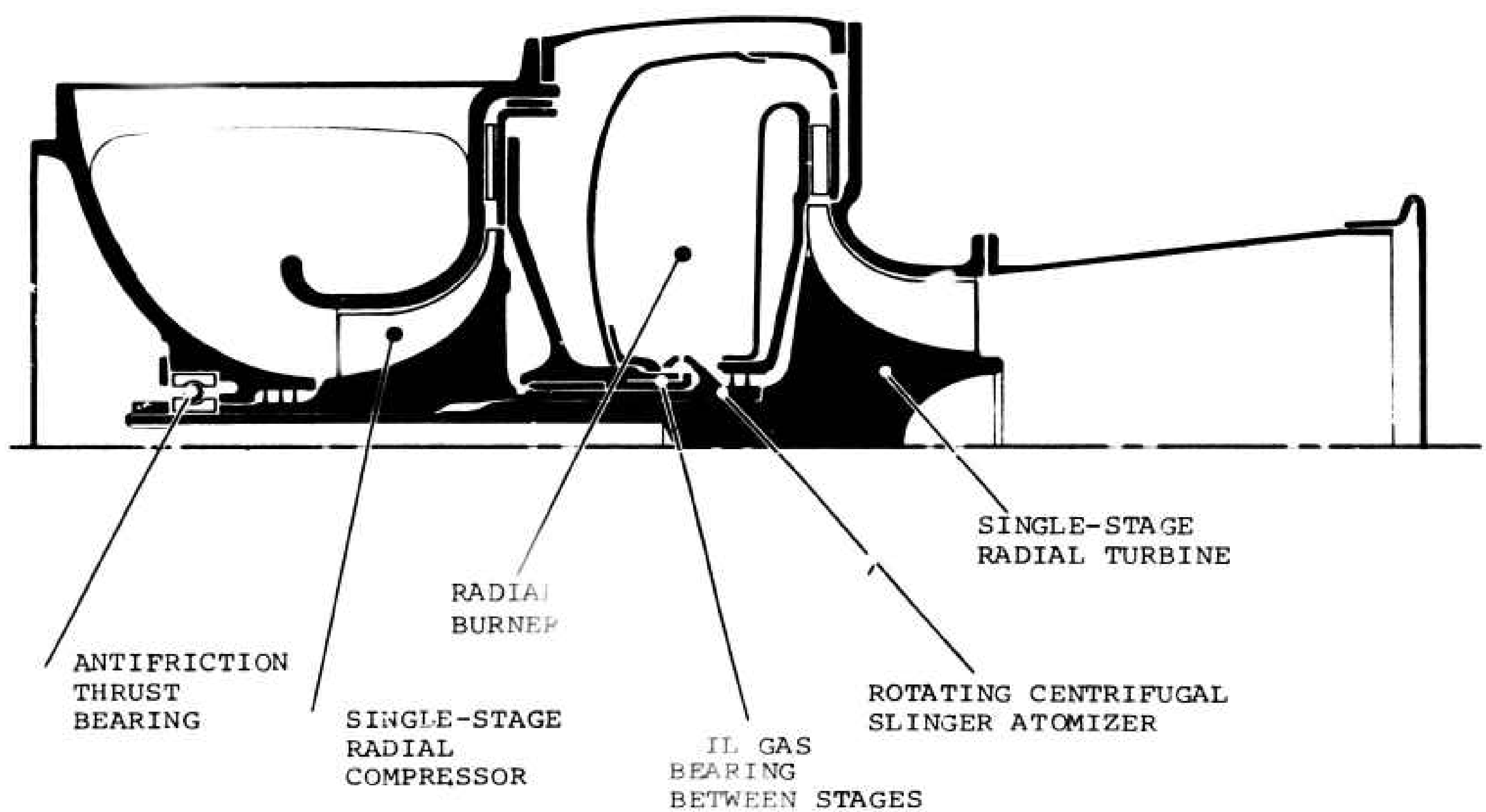


Figure 83. Technology Level II APU Configuration.

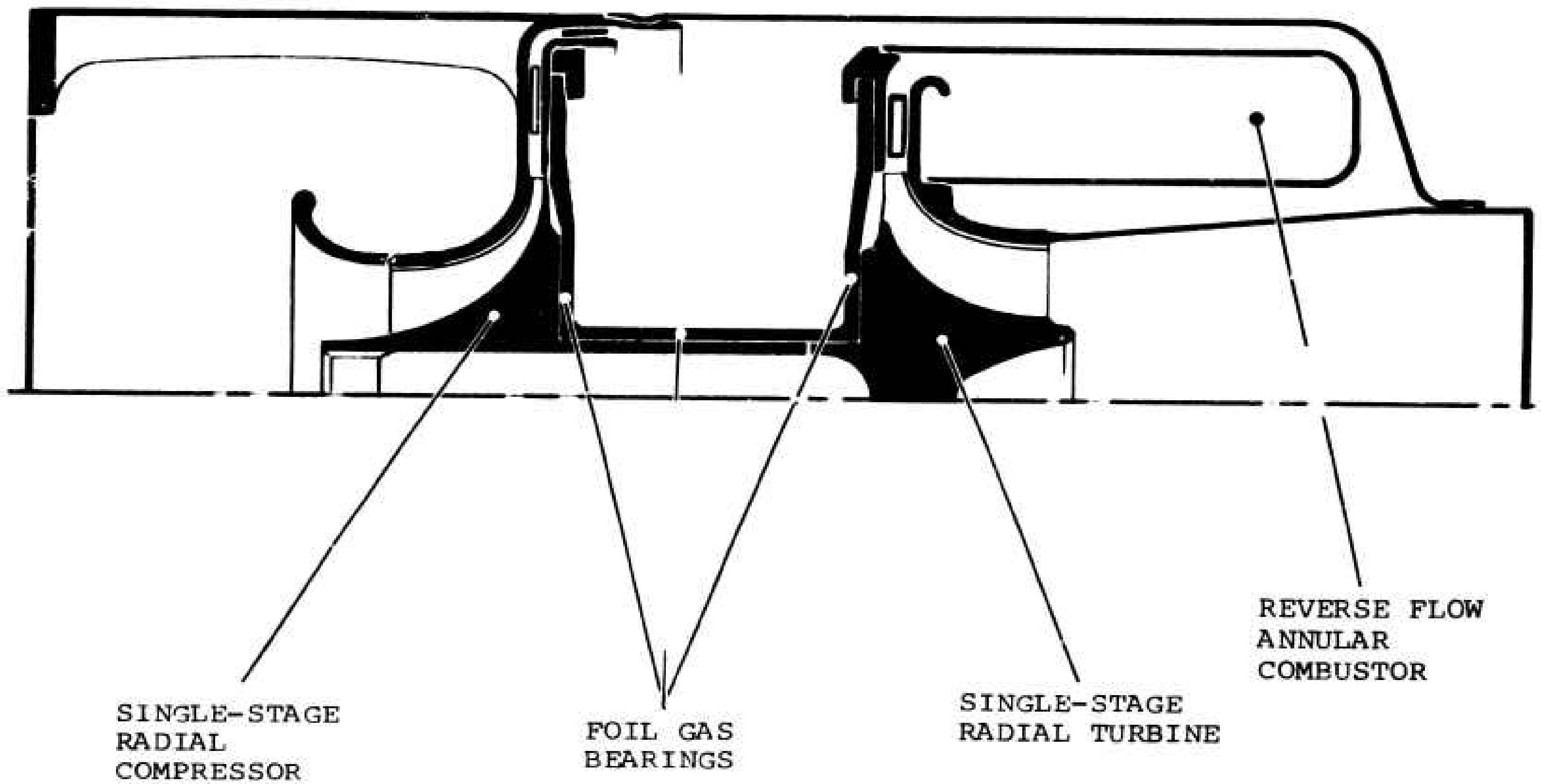


Figure 84. Technology Level III APU Configuration.

TABLE XXXV. SPS POWER REQUIREMENTS,** WITHOUT ECS

Technology Level I

System	Engine Start (shp)	Engine Start (W_B, P/P)	Hydraulic Check (W_B, P/P) (shp)	Electrical Check (W_B, P/P) (shp)
1.0.0.1	9.7	14.5/3.52	18.3	24.7
1.0.0.2	36.0	-	19.3	26.1
1.0.0.3	58.4	-	18.7	25.0
1.1.1.0	-	39.5/3.52	20.7/3.68	26.5/3.68
1.1.2.0	-	37.1/3.52	21.4/3.68	27.7/3.68
1.1.3.0	-	58.4/3.52	19.1/3.78	24.4/3.78
1.1.0.1	-	28.7/3.52	21.6/3.68	27.6/3.52
1.1.0.2	29.0	13.6/3.68	18.3	27.6/3.52 4.1
1.1.0.3	59.5	-	21.6/3.52 1.3	21.6
1.2.1.0	66.9	-	23.3	46.7
1.2.2.0	62.5	-	22.8	48.9
1.2.3.0	99.1	-	23.6	47.3
1.2.0.1	27.7	14.5/3.52	20.5	47.7
1.2.0.2	54.7	-	21.8	47.3
1.2.0.3	66.3	-	20.5	30.2
1.3.1.0	62.4	-	36.9	26.1
1.3.2.0	58.5	-	38.0	26.1
1.3.3.0	86.9	-	36.9	28.2
1.3.0.1	8.8	14.5/3.52	35.0	21.6
1.4.1.0	45.3*	-	25.2*	32.1*
1.4.2.0	43.4*	-	26.1*	33.8*
1.4.3.0	68.5*	-	25.2*	31.3*
1.4.0.1	16.5*	14.5/3.52	25.2*	32.4*
2.4.1.0	45.3*	-	25.2*	32.1*
2.4.2.0	43.9*	-	26.1*	33.8*
2.4.3.0	68.5*	-	25.2*	31.3*
2.4.0.1	16.5*	14.5/3.52	25.2*	32.4*

*Indicates fluid coupling in system.

**All power requirements are at the APU. Shaft horsepower includes APU gearbox losses except for systems with fluid coupling (shp is input to coupling).

TABLE XXXV - Continued				
Technology Level II				
	Engine Start		Hydraulic Check (W_B, P/P) (shp)	Electrical Check (W_B, P/P) (shp)
System	(shp)	(W_B, P/P)		
1.0.0.1	9.4	10.8/4.5	18.0	24.3
1.0.0.2	34.4	-	19.0	25.7
1.0.0.3	56.7	-	18.5	24.3
1.1.1.0	-	31.0/4.5	16.8/4.56	21.2/4.56
1.1.2.0	-	29.0/4.5	17.8/4.55	22.7/4.55
1.1.3.0	-	45.4/4.5	20.0/4.59	25.3/4.59
1.1.0.1	-	24.0/4.5	17.3/4.5	21.8/4.5
1.1.0.2	27.5	12.9/4.59	18.1	21.8/4.5 3.9
1.1.0.3	54.3	-	17.5/4.5 1.4	21.3
1.2.1.0	63.4	-	22.1	44.7
1.2.2.0	59.3	-	21.8	46.8
1.2.3.0	93.0	-	23.8	44.7
1.2.0.1	26.6	10.8/4.5	19.1	44.7
1.2.0.2	52.1	-	20.6	44.7
1.2.0.3	61.5	-	19.8	29.[illegible]
1.3.1.0	58.5	-	33.3	23.8
1.3.2.0	54.8	-	35.5	23.8
1.3.3.0	81.8	-	33.3	26.1
1.3.0.1	8.5	10.8/4.5	33.3	21.3
1.4.1.0	44.9*	-	24.8*	29.2*
1.4.2.0	42.0*	-	25.7*	30.6*
1.4.3.0	65.9*	-	24.8*	29.2*
1.4.0.1	15.9*	10.8/4.5	24.8*	29.5*
2.4.1.0	44.9*	-	24.8*	29.2*
2.4.2.0	42.0*	-	25.7*	30.6*
2.4.3.0	65.9*	-	24.8*	29.2*
2.4.0.1	15.9*	10.8/4.5	24.8*	29.5*

*Indicates fluid coupling in system.

TABLE XXXV - Concluded

Technology Level III

System	Engine Start (shp)	Engine Start (W_B, P/P)	Hydraulic Check (W_B, P/P) (shp)	Electrical Check (W_B, P/P) (shp)
1.0.0.1	8.7	8.8/5.6	17.5	23.4
1.0.0.2	33.9	-	18.5	24.7
1.0.0.3	52.9	-	18.0	23.4
1.1.1.0	-	22.3/5.6	12.9/5.76	16.2/5.76
1.1.2.0	-	22.3/5.6	13.4/5.76	17.0/5.76
1.1.3.0	-	35.0/5.6	12.9/5.76	16.2/5.76
1.1.0.1	-	16.9/5.6	14.3/5.6	16.6/5.6
1.1.0.2	27.2	8.5/5.78	17.6	16.6/5.6 3.3
1.1.0.3	50.9	-	13.2/5.6 1.4	20.9
1.2.1.0	56.4	-	20.6	40.1
1.2.2.0	55.4	-	20.4	41.9
1.2.3.0	84.6	-	22.7	40.1
1.2.0.1	22.9	8.8/5.6	17.3	40.1
1.2.0.2	48.4	-	19.3	40.1
1.2.0.3	56.8	-	19.3	27.3
1.3.1.0	51.5	-	31.6	23.5
1.3.2.0	50.4	-	30.0	24.2
1.3.3.0	77.2	-	31.5	22.8
1.3.0.1	8.1	8.8/5.6	28.6	20.9
1.4.1.0	40.4*	-	22.9*	28.8*
1.4.2.0	40.2*	-	23.8	30.1*
1.4.3.0	61.4*	-	22.9*	28.8*
1.4.0.1	14.0*	8.8/5.6	22.9*	28.8*
2.4.1.0	40.4*	-	22.9*	28.8*
2.4.2.0	40.2*	-	23.8*	30.1*
2.4.3.0	61.4*	-	22.9*	28.8*
2.4.0.1	14.0*	8.8/5.6	22.4*	28.8*

*Indicates fluid coupling in system.

TABLE XXXVI. SPS POWER REQUIREMENTS,** WITH ECS

Technology Level I

System	Engine Start (shp)	Engine Start (W_B, P/P)	Hydraulic Check (W_B, P/P) (shp)	Electrical Check (W_B, P/P) (shp)
1.0.0.1	9.7	13.6/3.68	23.0/3.52 18.3	23.0/3.52 24.7
1.0.0.2	36	-	23.0/3.52 19.3	23.0/3.52 26.1
1.0.0.3	58.4	-	23.0/3.52 18.7	23.0/3.52 25.0
1.1.1.0	-	37.8/3.68	43.7/3.52	48.6/3.52
1.1.2.0	-	35.7/3.68	43.4/3.52	51.0/3.52
1.1.3.0	-	58.4/3.52	42.1/3.52	49.6/3.52
1.1.0.1	-	28.1/3.68	44.6/3.52	50.6/3.52
1.1.0.2	29.0	13.6/3.68	23.0/3.52 18.3	50.6/3.52 4.1
1.1.0.3	59.5	-	44.6/3.52 1.1	23.0/3.52 21.6
1.2.1.0	65.5	-	27.9	118.7
1.2.2.0	62.5	-	23.0/3.52 22.8	23.0/3.52 49.9
1.2.3.0	99.1	-	23.0/3.52 23.6	23.0/3.52 47.3
1.2.0.1	27.7	13.3/3.68	23.0/3.52 20.5	23.0/3.52 47.3
1.2.0.2	54.7	-	23.0/3.52 21.8	23.0/3.52 47.3
1.2.0.3	66.3	-	23.0/3.52 20.5	23.0/3.52 30.2
1.3.1.0	62.2	-	97.9	98.5
1.3.2.0	58.5	-	23.0/3.52 38.4	23.0/3.52 26.1
1.3.3.0	86.9	-	23.0/3.52 37.1	23.0/3.52 28.2
1.3.0.1	8.8	13.3/3.68	23.0/3.52 35.1	23.0/3.52 21.6
1.4.0.1	46.0*	-	71.1*	81.5*
1.4.2.0	43.9*	-	23.0/3.52 26.2	23.0/3.52 33.8
1.4.3.0	68.5	-	23.0/3.52 25.2	23.0/3.52 32.0
1.4.0.1	16.3	13.3/3.68	23.0/3.52	23.0/3.52
2.4.1.0	46.0*	-	71.1*	81.5
2.4.2.0	43.9	-	23.0/3.52 26.2*	23.0/3.52 33.8*
2.4.3.0	68.5	-	23.0/3.52 25.2*	23.0/3.52 32.0*
2.4.0.1	16.3*	13.3/3.68	23.0/3.52 25.2*	23.0/3.52 32.6*

*Indicates fluid coupling in system.

**All power requirements are at the APU. Shaft horsepower includes APU gearbox losses except for systems with fluid coupling (shp is input to coupling).

TABLE XXXVI - Continued

Technology Level II

System	Engine Start (shp)	Engine Start (W_B, P/P)	Hydraulic Check (W_B, P/P) (shp)	Electrical Check (W_B, P/P) (shp)
1.0.0.1	9.4	10.7/4.54	14.3/4.5 18.1	14.3/4.5 24.3
1.0.0.2	34.4	-	14.3/4.5 19.0	14.3/4.5 25.7
1.0.0.3	56.7	-	14.3/4.5 18.2	14.3/4.5 24.3
1.1.1.0	-	31.0/4.5	31.7/4.5	36.2/4.5
1.1.2.0	-	28.7/4.54	33.6/4.5	38.9/4.5
1.1.3.0	-	45.4/4.5	31.4/4.54	35.9/4.54
1.1.0.1	-	23.5/4.58	31.6/4.5	36.1/4.5
1.1.0.2	2.75	12.8/4.61	14.3/4.5 18.1	36.1/4.5 3.9
1.1.0.3	54.3	-	31.8/4.5 1.4	14.3/4.5 21.3
1.2.1.0	63.4	-	82.2	95.0
1.2.2.0	59.3	-	14.3/4.5 21.8	14.3/4.5 46.8
1.2.3.0	93.0	-	14.3/4.5 23.8	14.3/4.5 44.7
1.2.0.1	26.6	10.7/4.54	14.3/4.5 19.1	14.3/4.5 44.7
1.2.0.2	52.1	-	14.3/4.5 20.6	14.3/4.5 44.7
1.2.0.3	61.5	-	14.3/4.5 19.8	14.3/4.5 29.1
1.3.1.0	58.5	-	85.8	90.4
1.3.2.0	54.8	-	14.3/4.5 35.5	14.3/4.5 23.8
1.3.3.0	81.8	-	14.3/4.5 33.3	14.3/4.5 26.1
1.3.0.1	8.5	10.8/4.5	14.3/4.5 33.3	14.3/4.5 21.3
1.4.1.0	44.9*	-	63.7*	70.3*
1.4.2.0	42.0*	-	14.3/4.5 25.7*	14.3/4.5 30.6*
1.4.3.0	65.9*	-	14.3/4.5 24.8*	14.3/4.5 29.2*
1.4.0.1	15.9*	10.7/4.54	14.3/4.5 24.8*	14.3/4.5 29.5*
2.4.1.0	44.9*	-	63.7*	70.3*
2.4.2.0	42.0*	-	14.3/4.5 25.7*	14.3/4.5 30.6*
2.4.3.0	65.9*	-	14.3/4.5 24.8*	14.3/4.5 29.2*
2.4.0.1	15.9*	10.7/4.54	14.3/4.5 24.8*	14.3/4.5 29.5*

*Indicates fluid coupling in system.

TABLE XXXVI - Concluded				
Technology Level III				
System	Engine Start (shp)	Engine Start (W_B, P/P)	Hydraulic Check (W_B, P/P) (shp)	Electrical Check (W_B, P/P) (shp)
1.0.0.1	8.7	8.8/5.6	9.8/5.6 17.5	9.8/5.6 23.4
1.0.0.2	33.9	-	9.8/5.6 18.5	9.8/5.6 24.7
1.0.0.3	52.9	-	9.8/5.6 18.0	9.8/5.6 23.4
1.1.1.0	-	22.3/5.6	23.0/5.6	26.2/5.6
1.1.2.0	-	22.3/5.6	23.6/5.6	27.0/5.6
1.1.3.0	-	35.0/5.6	22.7/5.76	26.0/5.76
1.1.0.1	-	16.4/5.84	23.0/5.6	26.2/5.6
1.1.0.2	27.3	7.8/5.84	9.8/5.6 17.6	26.2/5.6 3.3
1.1.0.3	50.9	-	23.0/5.6 1.4	9.8/5.6 20.9
1.2.1.0	56.4	-	75.4	82.9
1.2.2.0	55.4	-	9.8/5.6 20.4	9.8/5.6 41.9
1.2.3.0	84.6	-	9.8/5.6 22.7	9.8/5.6 40.1
1.2.0.1	22.9	8.8/5.6	9.8/5.6 17.3	9.8/5.6 40.1
1.2.0.2	48.4	-	9.8/5.6 19.3	9.8/5.6 40.1
1.2.0.3	56.8	-	9.8/5.6 19.3	9.8/5.6 27.3
1.3.1.0	51.5	-	69.8	77.7
1.3.2.0	50.8	-	9.8/5.6 30.0	9.8/5.6 24.2
1.3.3.0	77.2	-	9.8/5.6 31.5	9.8/5.6 22.8
1.3.0.1	8.1	8.8/5.6	9.8/5.6 28.6	9.8/5.6 20.9
1.4.1.0	39.9*	-	53.8*	59.9*
1.4.2.0	40.2*	-	9.8/5.6 23.8*	9.8/5.6 30.1*
1.4.3.0	61.4*	-	9.8/5.6 22.9*	9.8/5.6 28.8*
1.4.0.1	14.0	8.8/5.6	9.8/5.6 22.9*	9.8/5.6 29.1*
2.4.1.0	39.9*	-	53.8*	59.9*
2.4.2.0	40.2*	-	9.8/5.6 23.8*	9.8/5.6 30.1*
2.4.3.0	61.4*	-	9.8/5.6 22.9*	9.8/5.6 28.8*
2.4.0.1	14.0*	8.8/5.6	9.8/5.6 22.9*	9.8/5.6 29.1*

*Indicates fluid coupling in system.

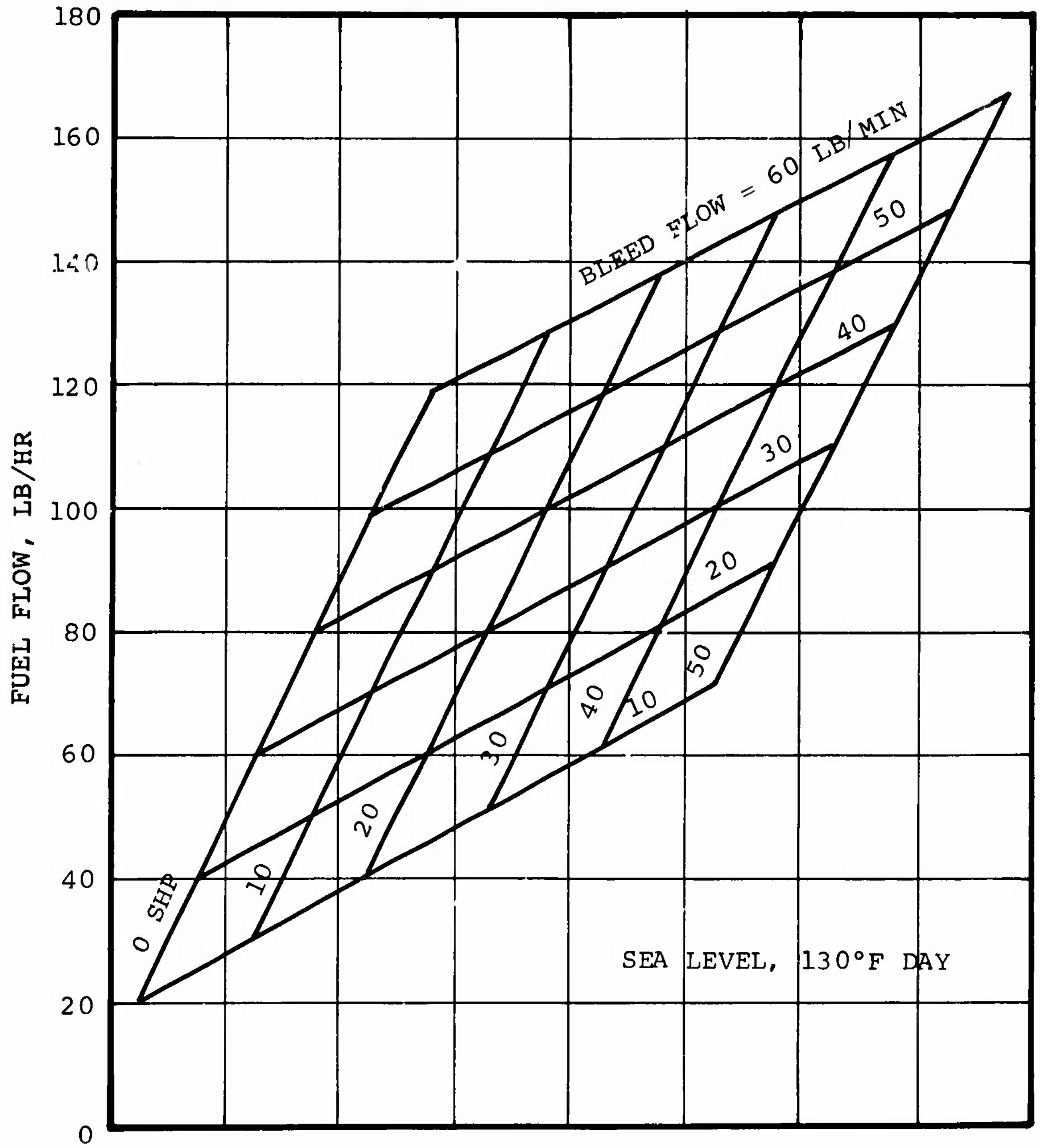


Figure 85. Design-Point Fuel Flow, Bleed/Shaft APU, Nonregenerated, Technology Level I.

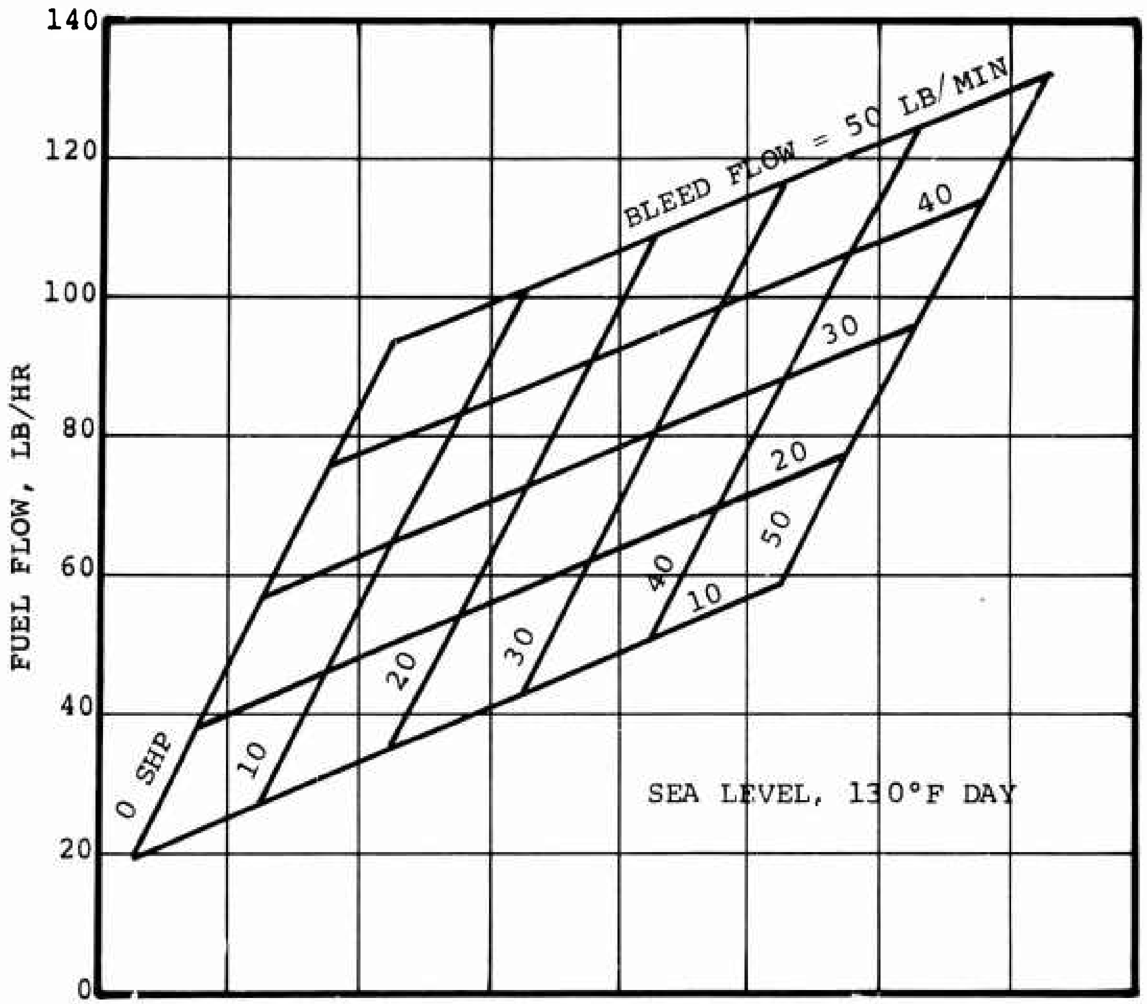


Figure 86. Design-Point Fuel Flow, Bleed/Shaft APU, Nonregenerated, Technology Level II.

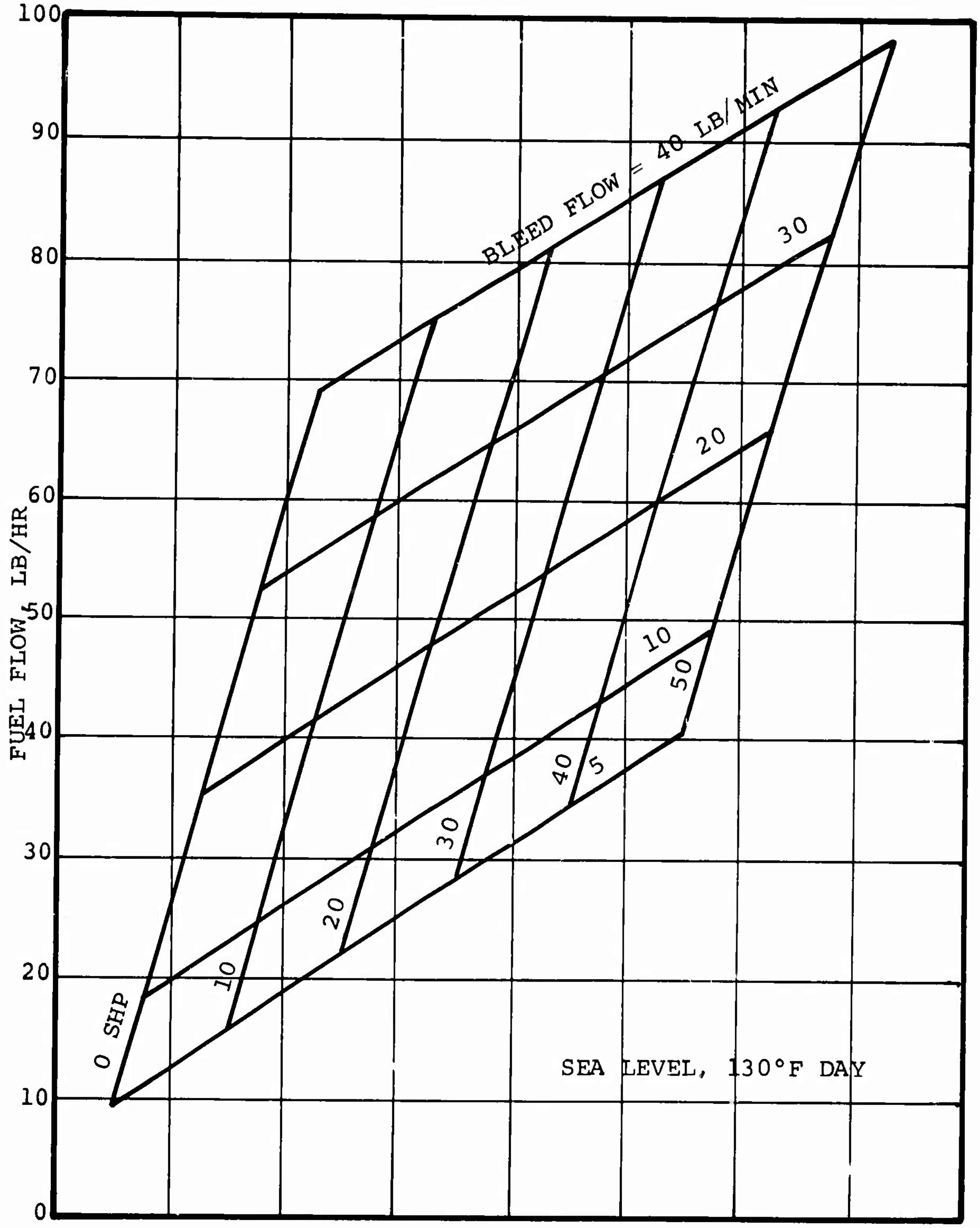


Figure 87. Design-Point Fuel Flow, Bleed/Shaft APU, Nonregenerated, Technology Level III.

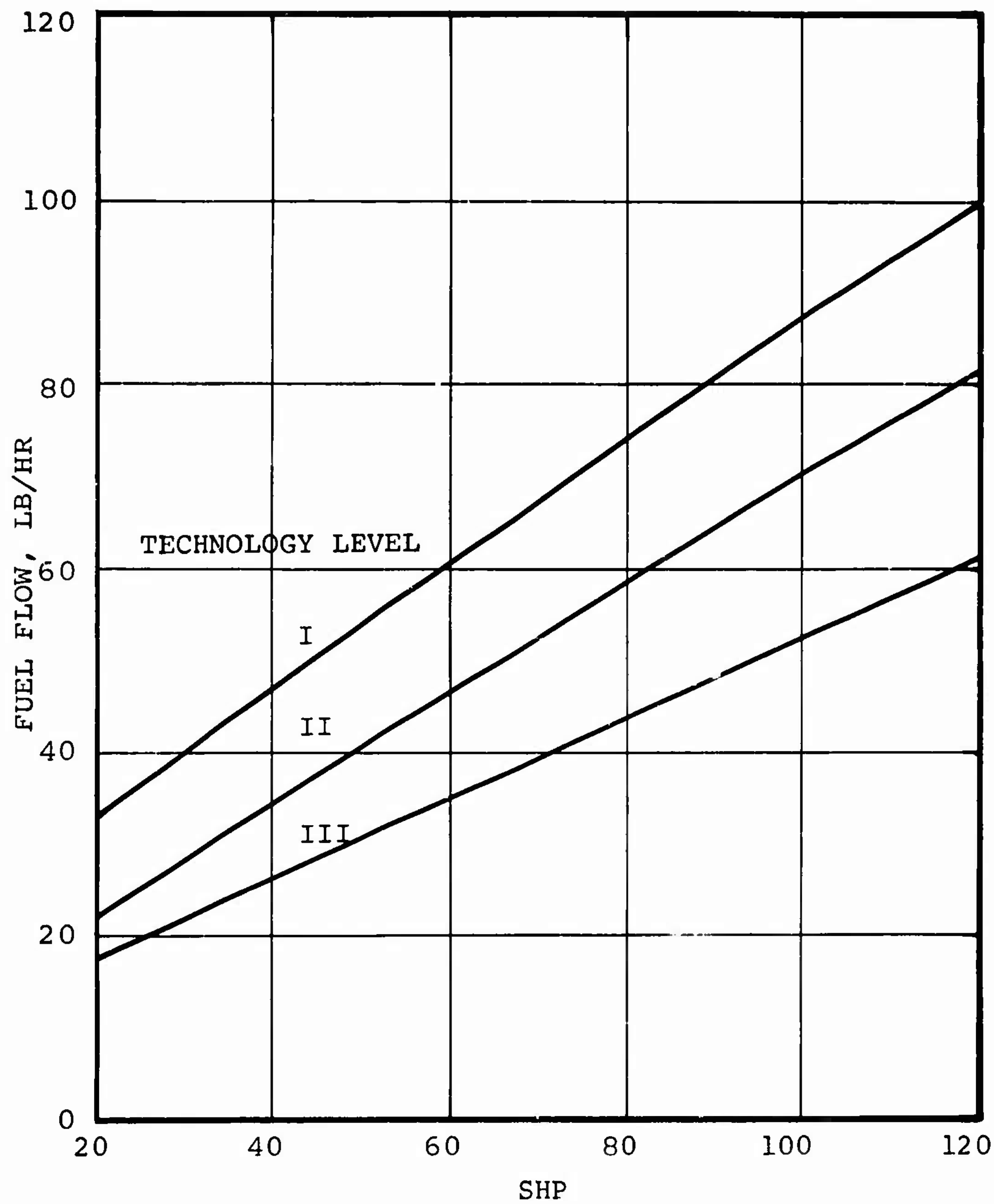


Figure 88. APU Design-Point Fuel Flow, Shaft Power Only, Nonregenerated.

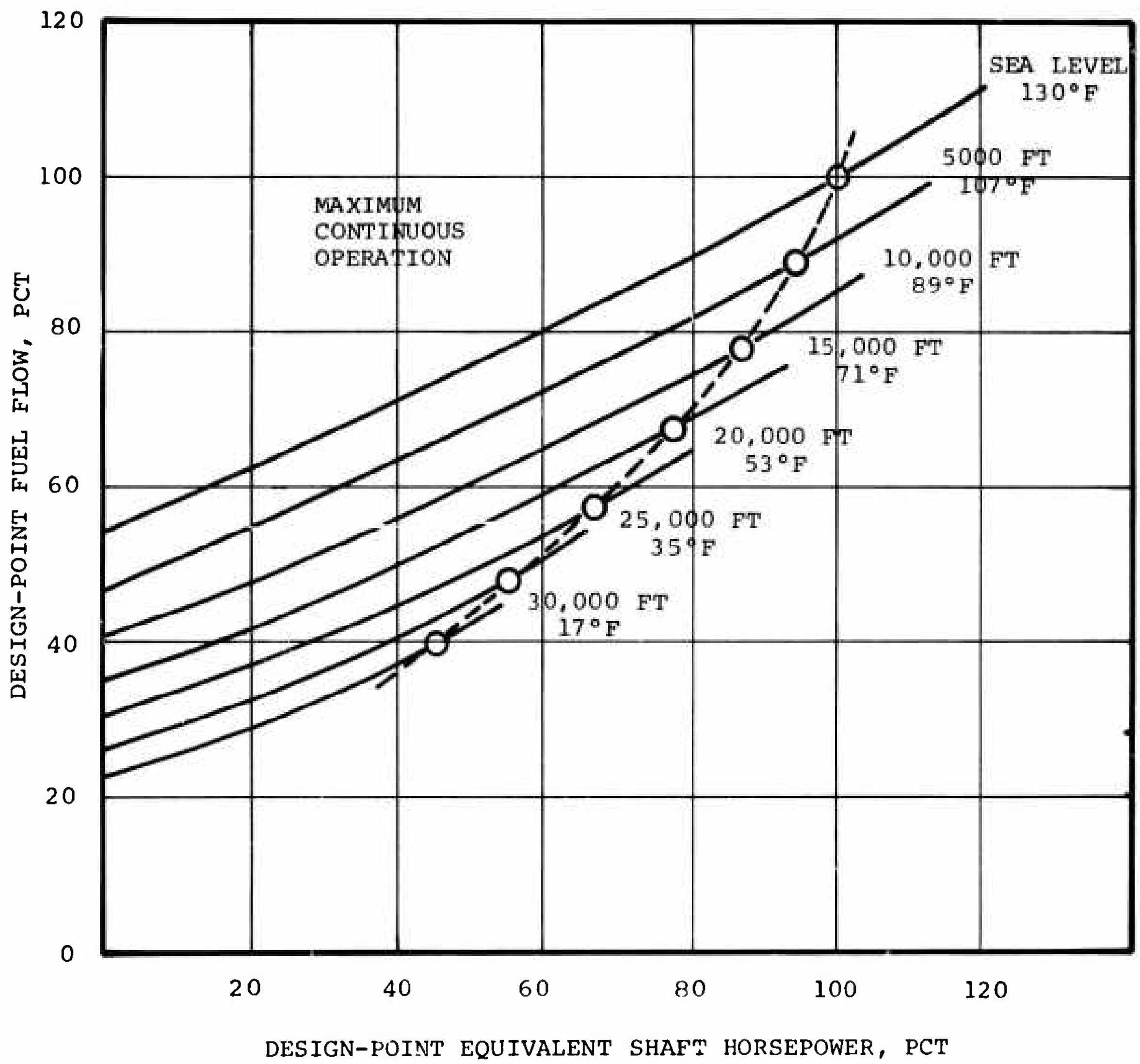


Figure 89. Estimated Off-Design APU Performance.

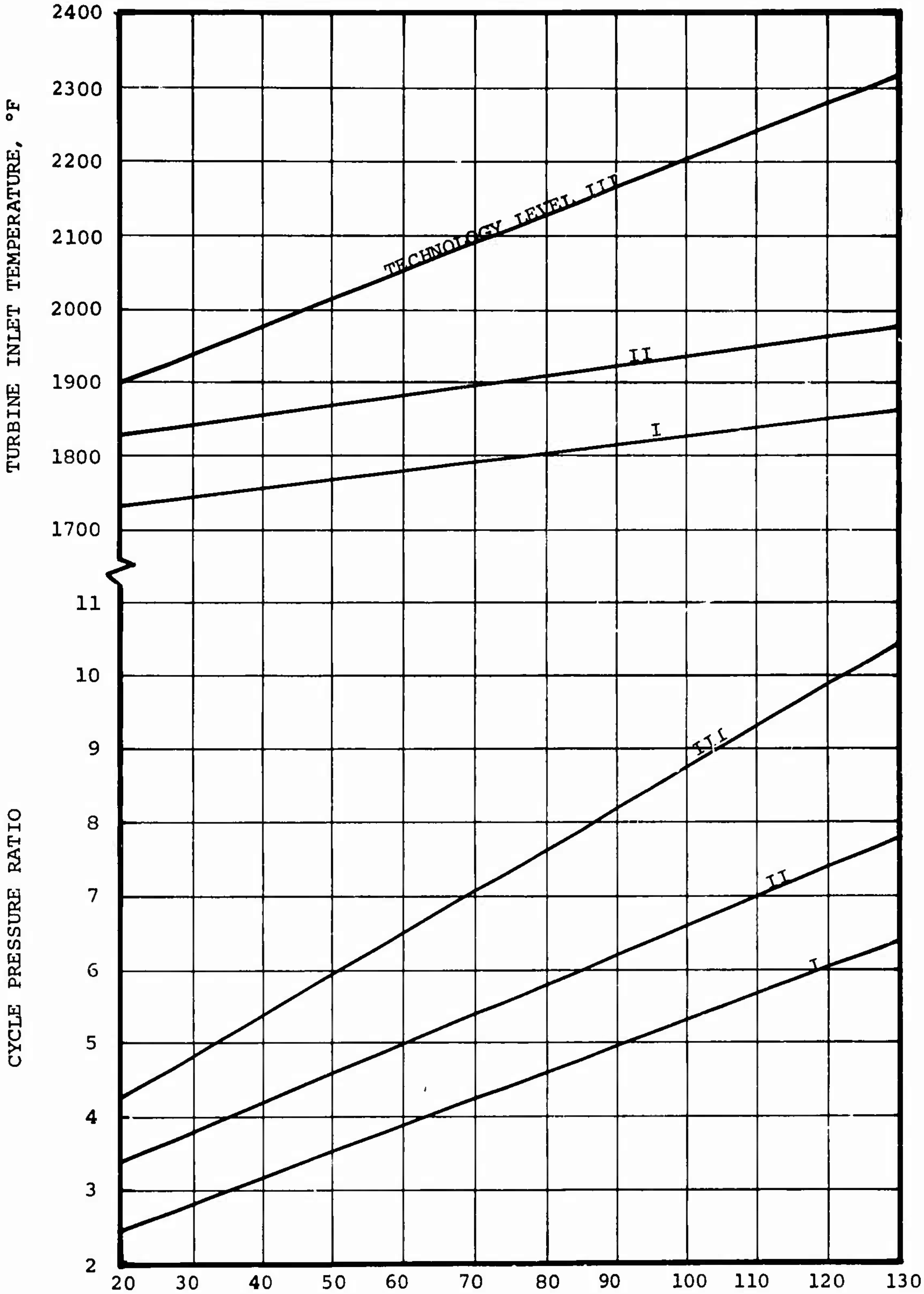


Figure 90. Cycle P/P and TIT vs Design eshp.

TABLE XXXVII. MAXIMUM APU BLEED PRESSURE RATIOS		
Technology Level		
I	II	III
3.52	4.50	5.60

Figure 90 provided a guide for generating APU sizing data (weight and volume) in conjunction with the established APU configurations (Figures 82, 83, and 84). Figure 90 also provided basic cycle data for the design-point fuel consumption calculations.

Figures 91 through 98 are the weight and volume curves for nonregenerated bleed/shaft and pure shaft APU, including the required accessories (fuel controls, igniters, bleed valves, etc.). Figures 99 through 103 are curves of the basic APU (nonregenerated) gearbox weight and volume. The basic gearbox consists of the mounting pad, fuel control, and starter pads. Figures 104 and 105 are curves of weight and volume increments, respectively for adding hydraulic pumps or generators to the basic APU gearbox. The weight increment for a fluid coupling is shown in Figure 106. If a PTO pad is required on the APU gearbox, Figure 105 can determine the weight and volume increments by equating the power transmitted through the PTO pad to an equivalent generator rating.

The total weight of the APU, with accessories and gearbox, was calculated for each system from Tables XXXV and XXXVI, to determine power levels, and from Figures 10 through 36, to determine the APU gearbox configuration.

6.7.4 APU Starting System

An analysis was conducted to determine the most feasible self-contained APU system for the ambient conditions and APU sizes of the candidate systems. Two main types were considered:

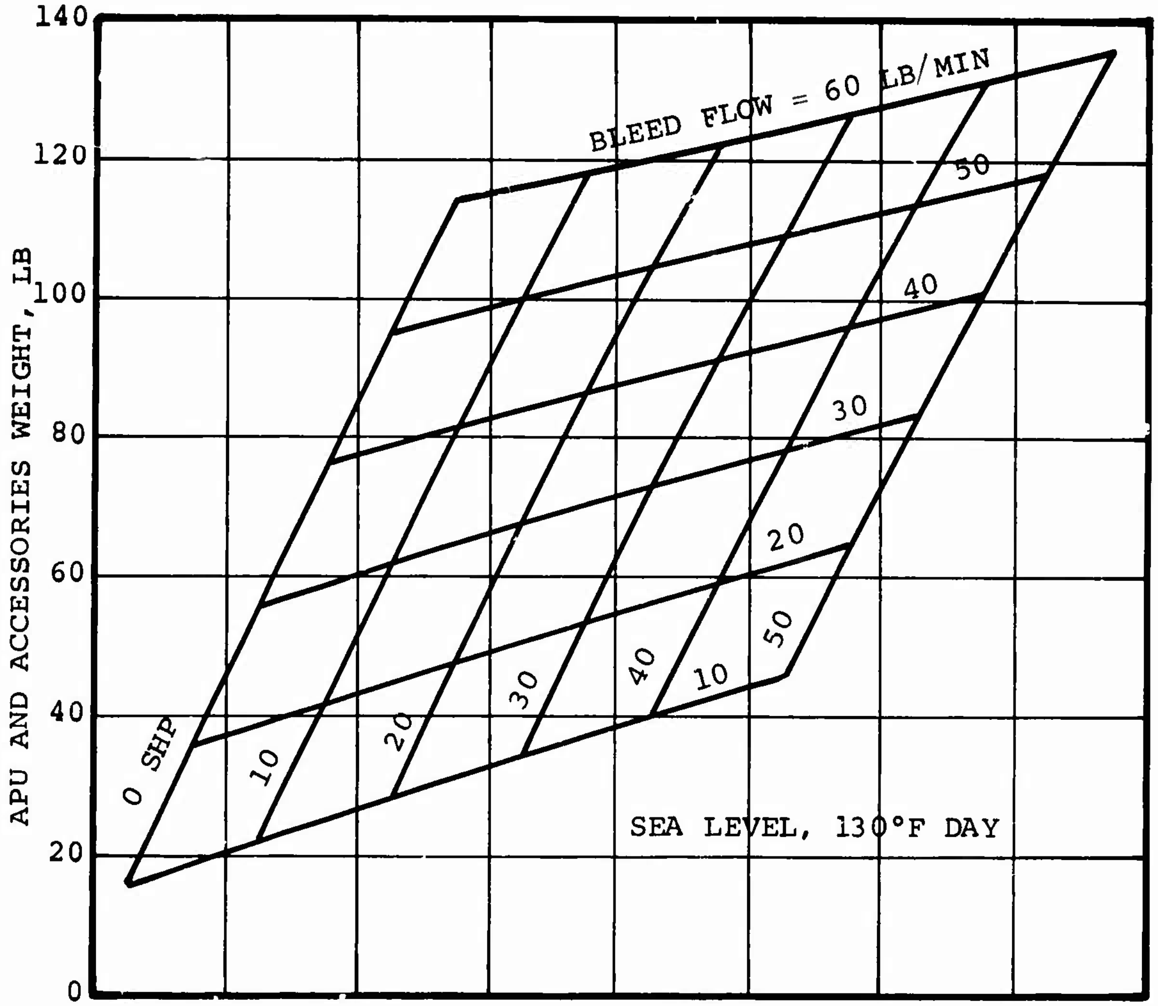


Figure 91. APU and Accessories Weight, Bleed/Shaft APU, Nonregenerated. Technology Level I.

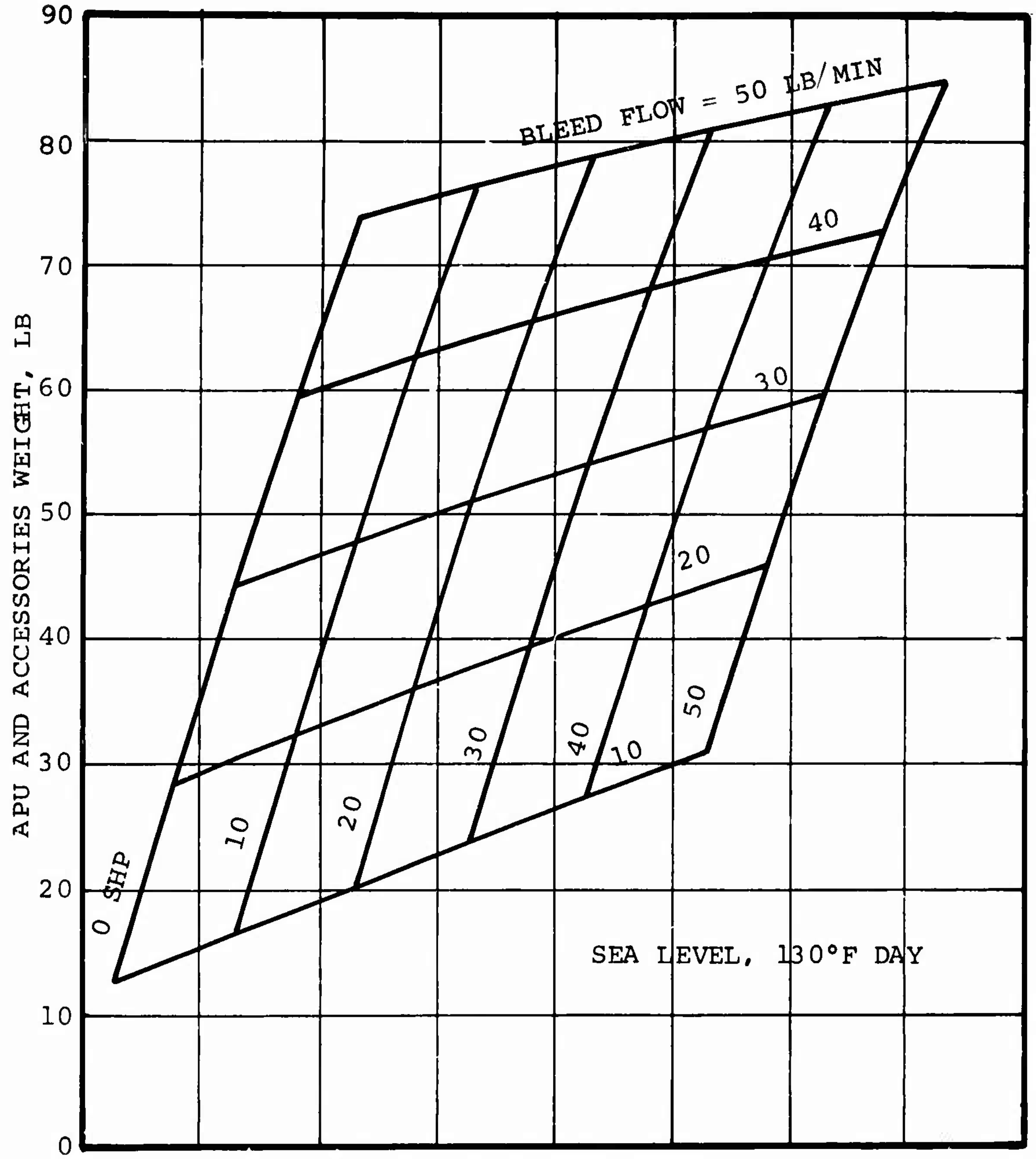


Figure 92. APU and Accessories Weight, Bleed/Shaft APU, Nonregenerated, Technology Level II.

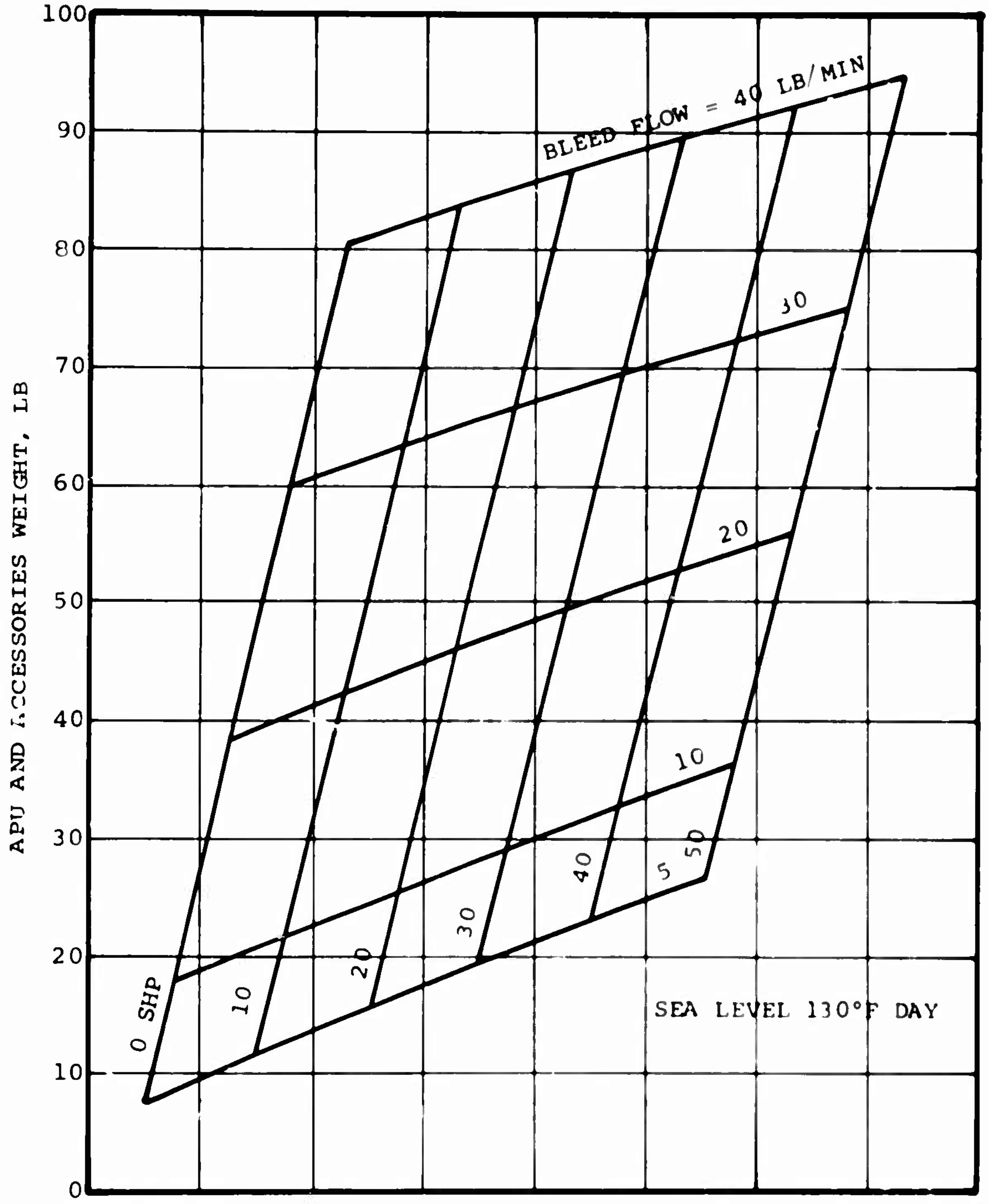


Figure 93. APU and Accessories Weight, Bleed/Shaft APU, Nonregenerated, Technology Level III.

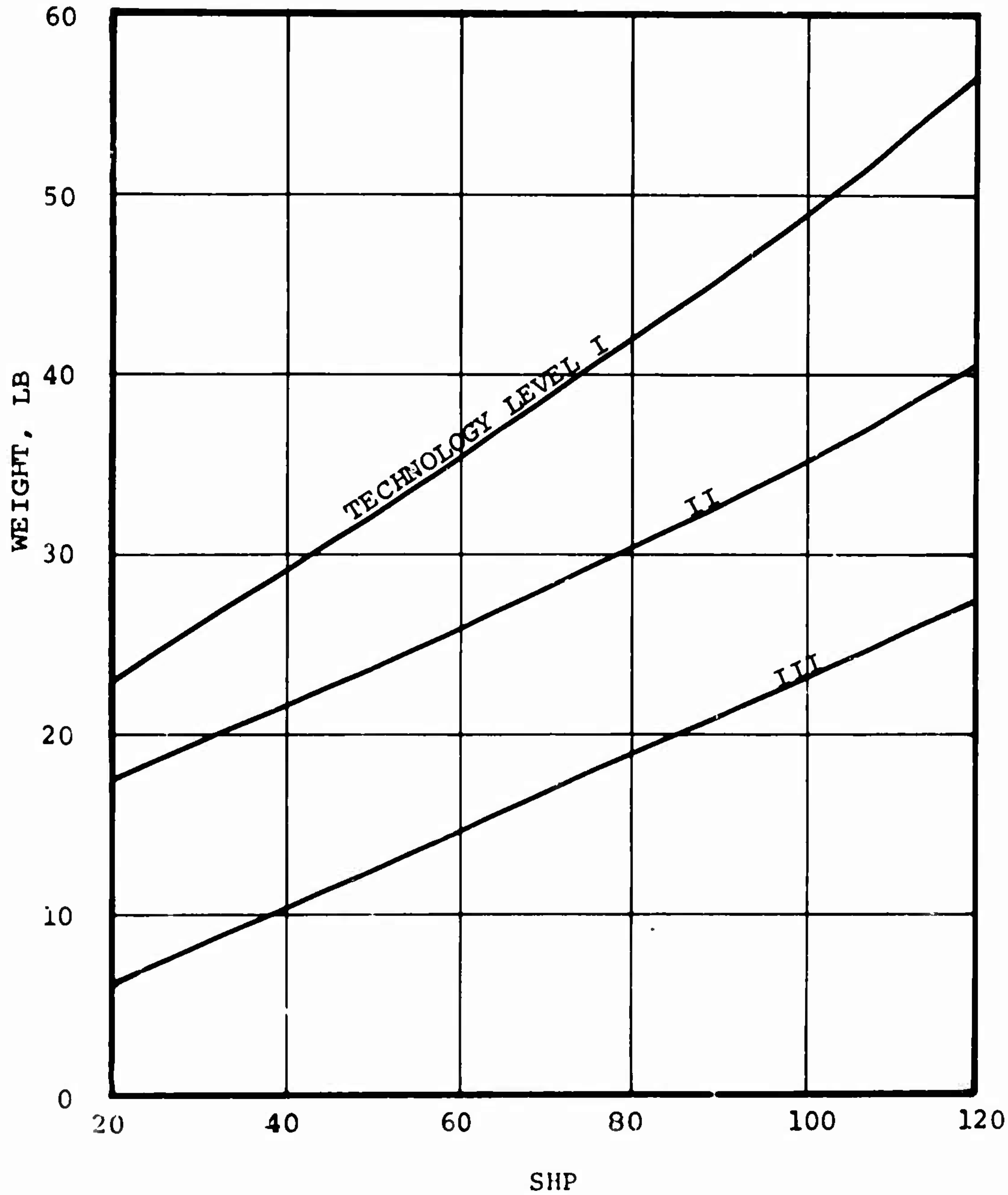


Figure 94. APU and Accessories Weight, Shaft-Power-Only APU, Nonregenerated.

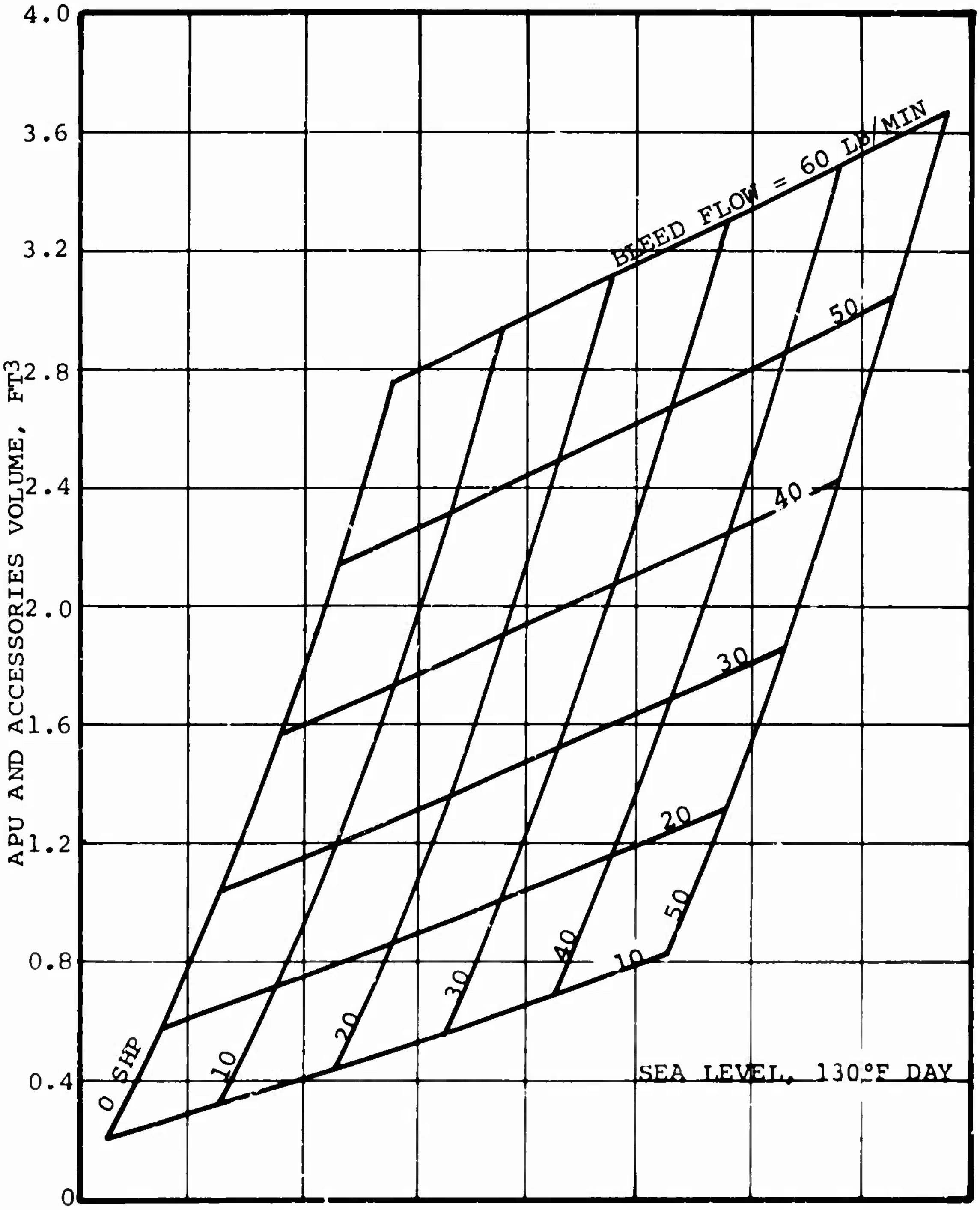


Figure 95. APU and Accessories Volume, Bleed/Shaft, Nonregenerated, Technology Level I.

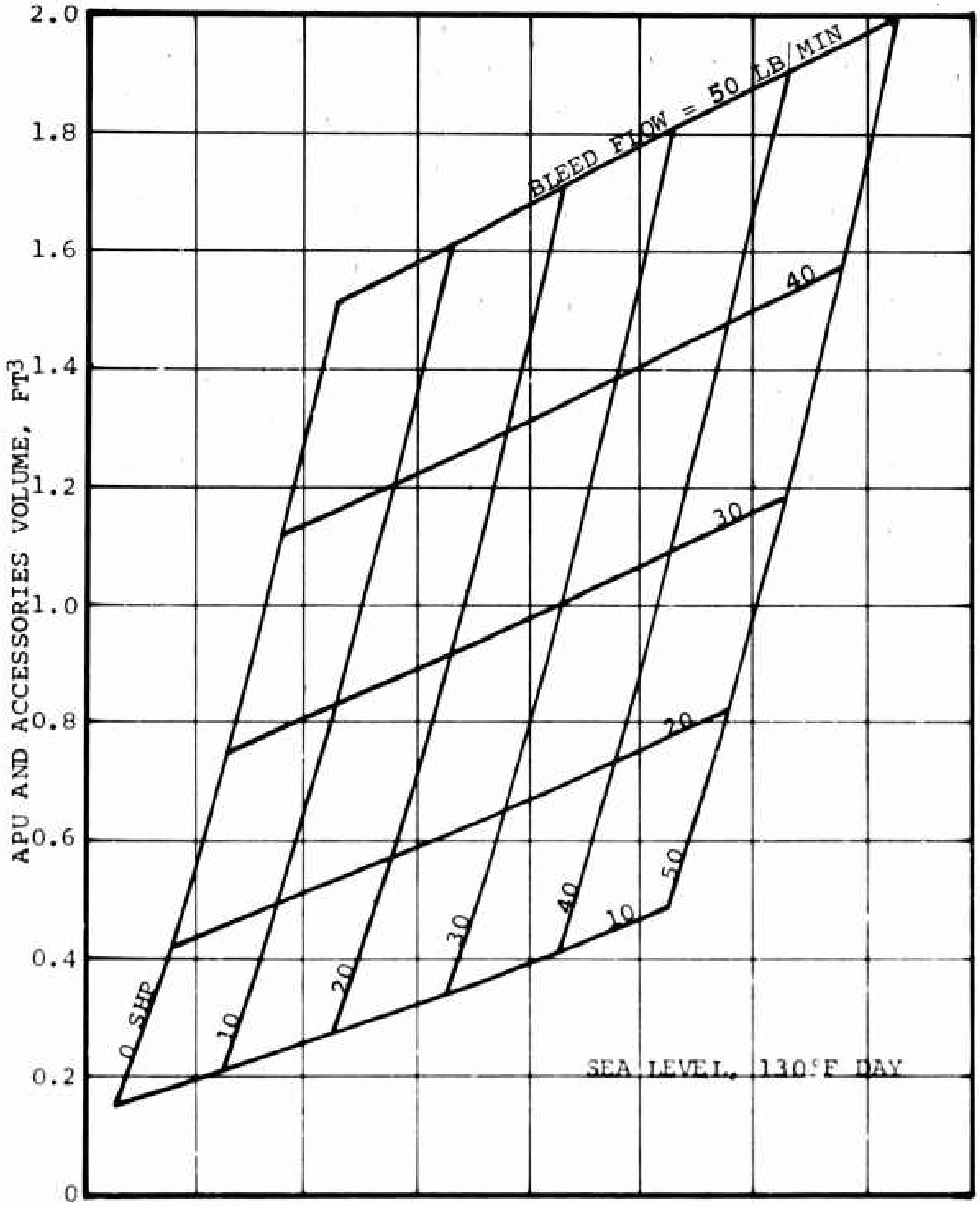


Figure 96. APU and Accessories Volume, Bleed/Shaft, Nonregenerated, Technology Level II.

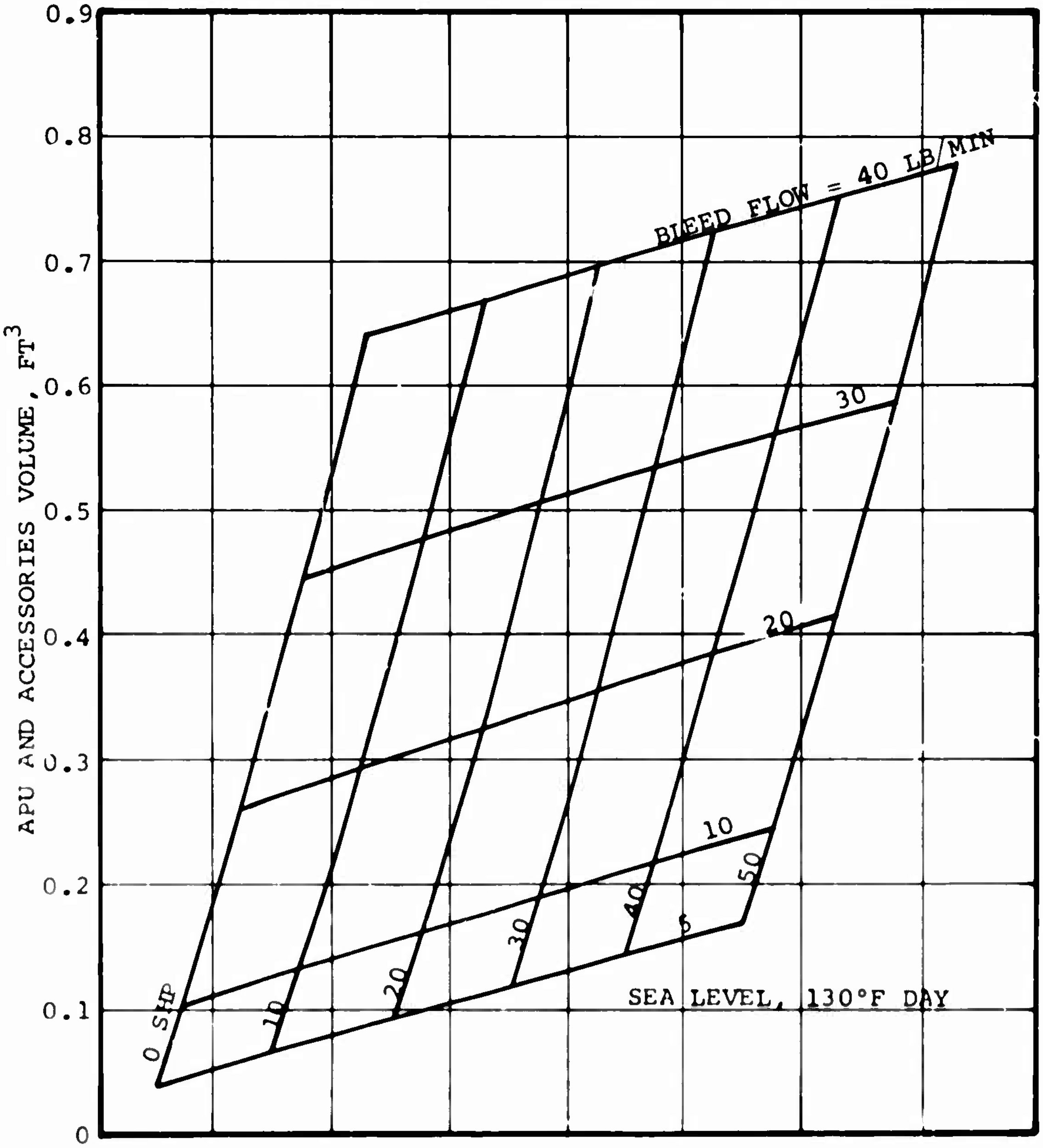


Figure 97. APU and Accessories Volume, Bleed/Shaft, Nonregenerated, Technology Level III.

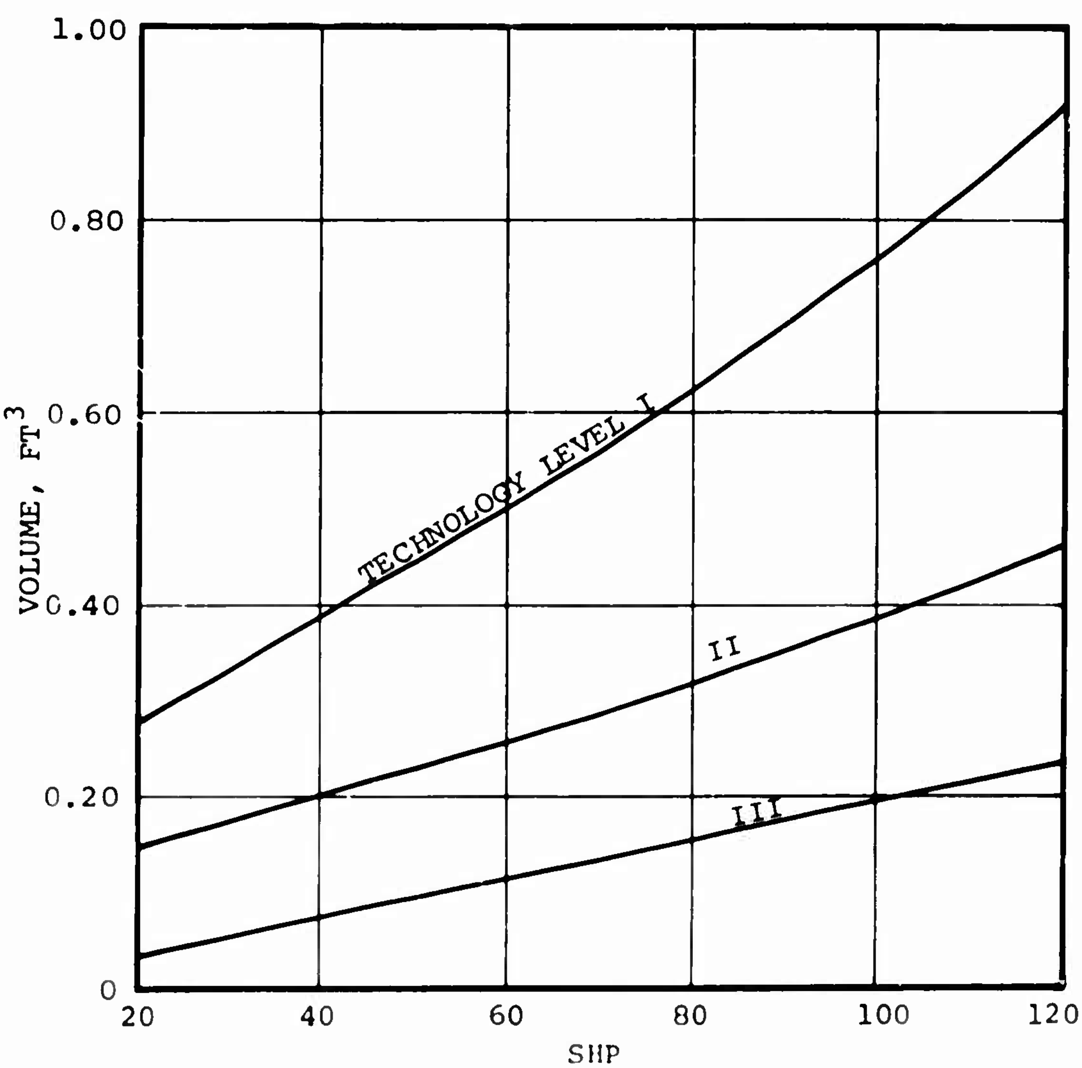


Figure 98. APU and Accessories Volume, Shaft-Power-Only APU, Nonregenerated.

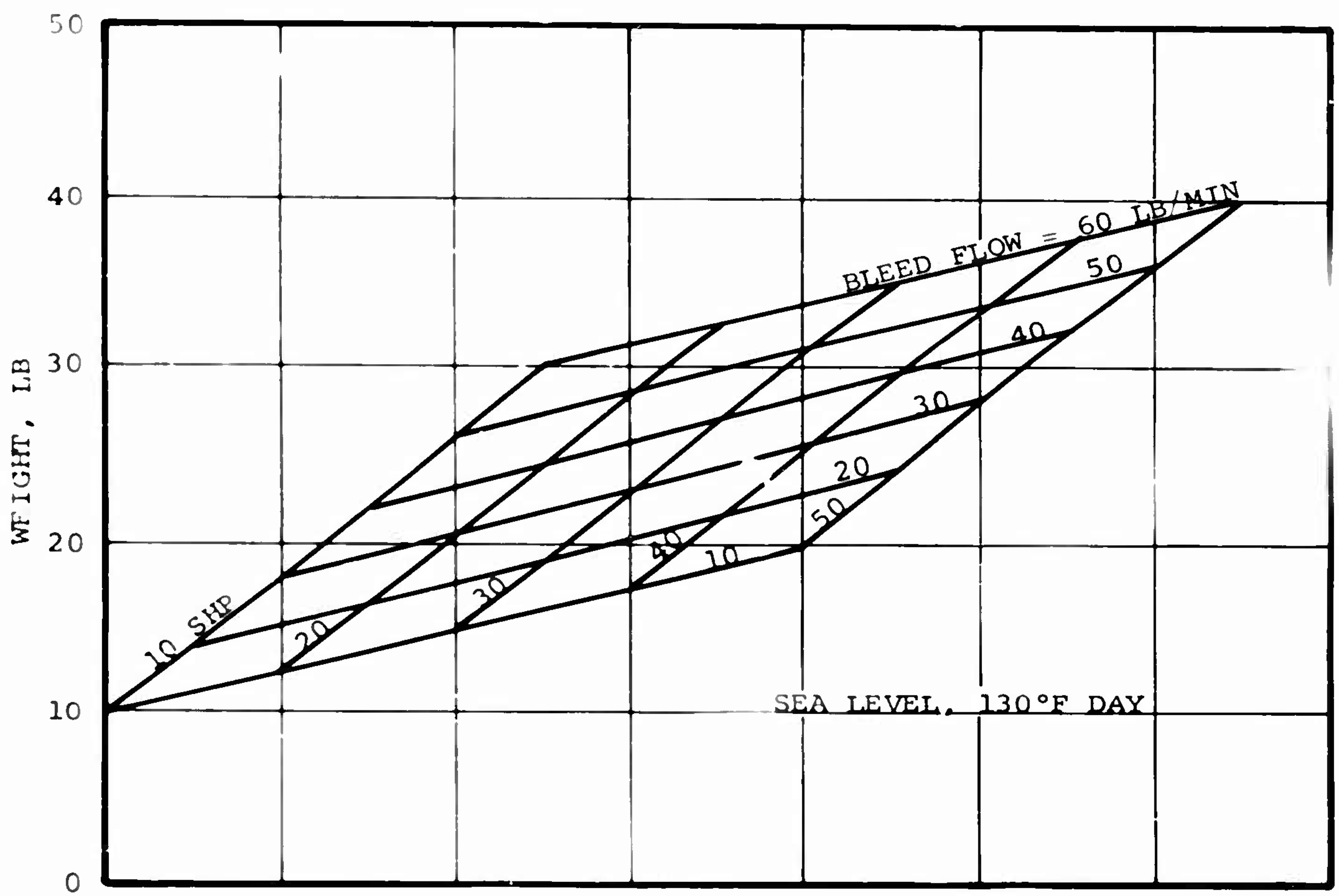


Figure 99. APU Basic Gearbox Weight, Nonregenerated, Technology Level I.

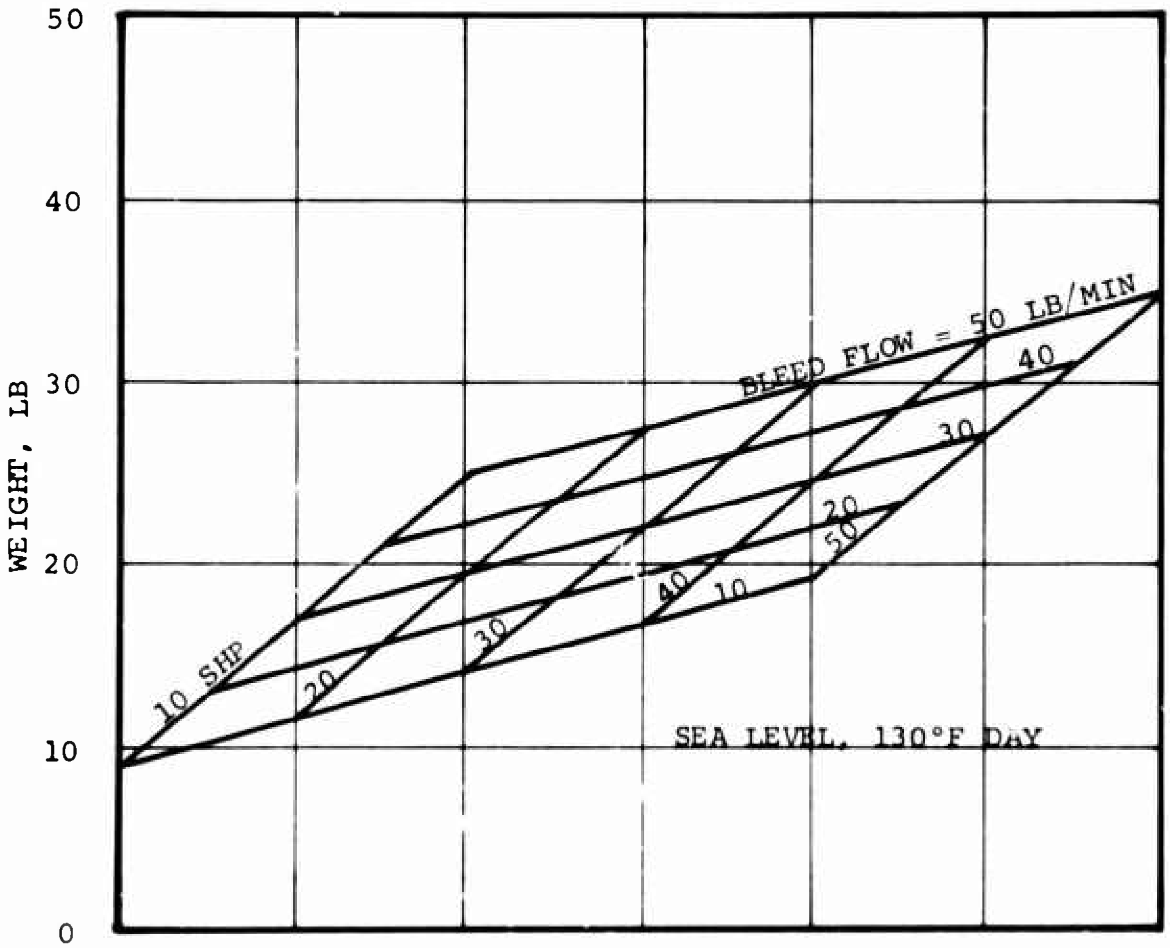


Figure 100. APU Basic Gearbox Weight, Nonregenerated, Technology Level II.

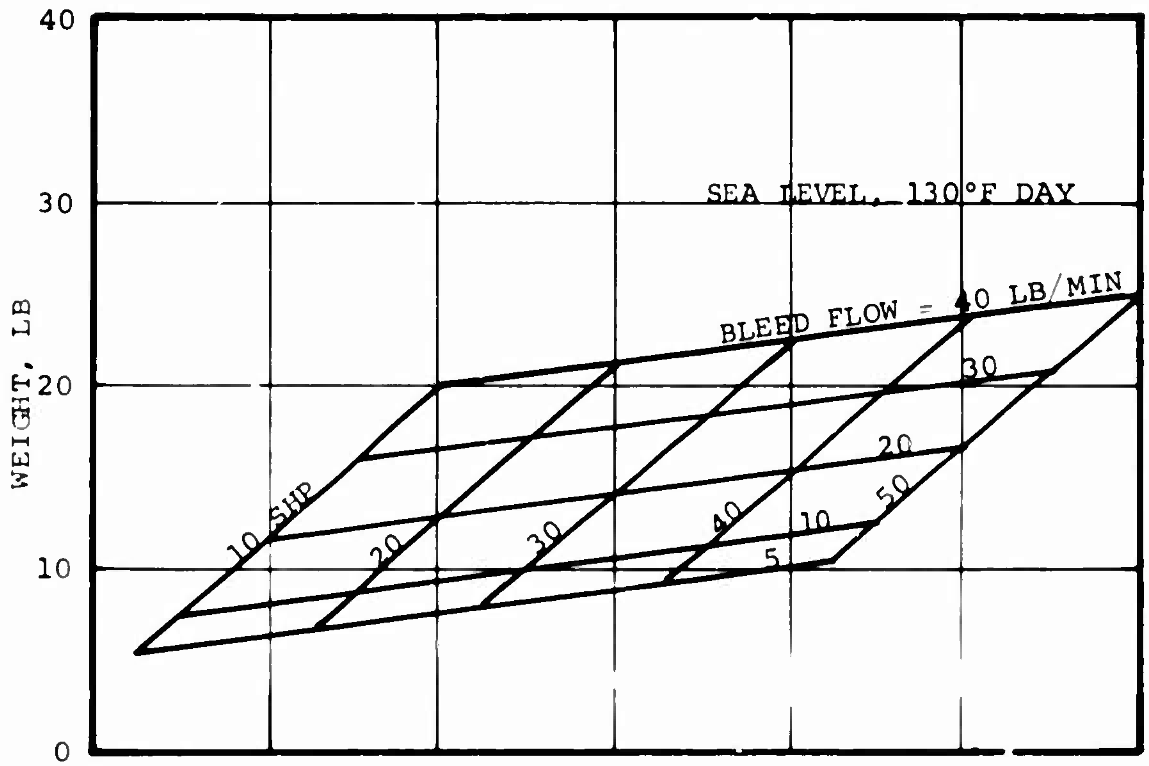


Figure 101. APU Basic Gearbox Weight, Nonregenerated, Technology Level III.

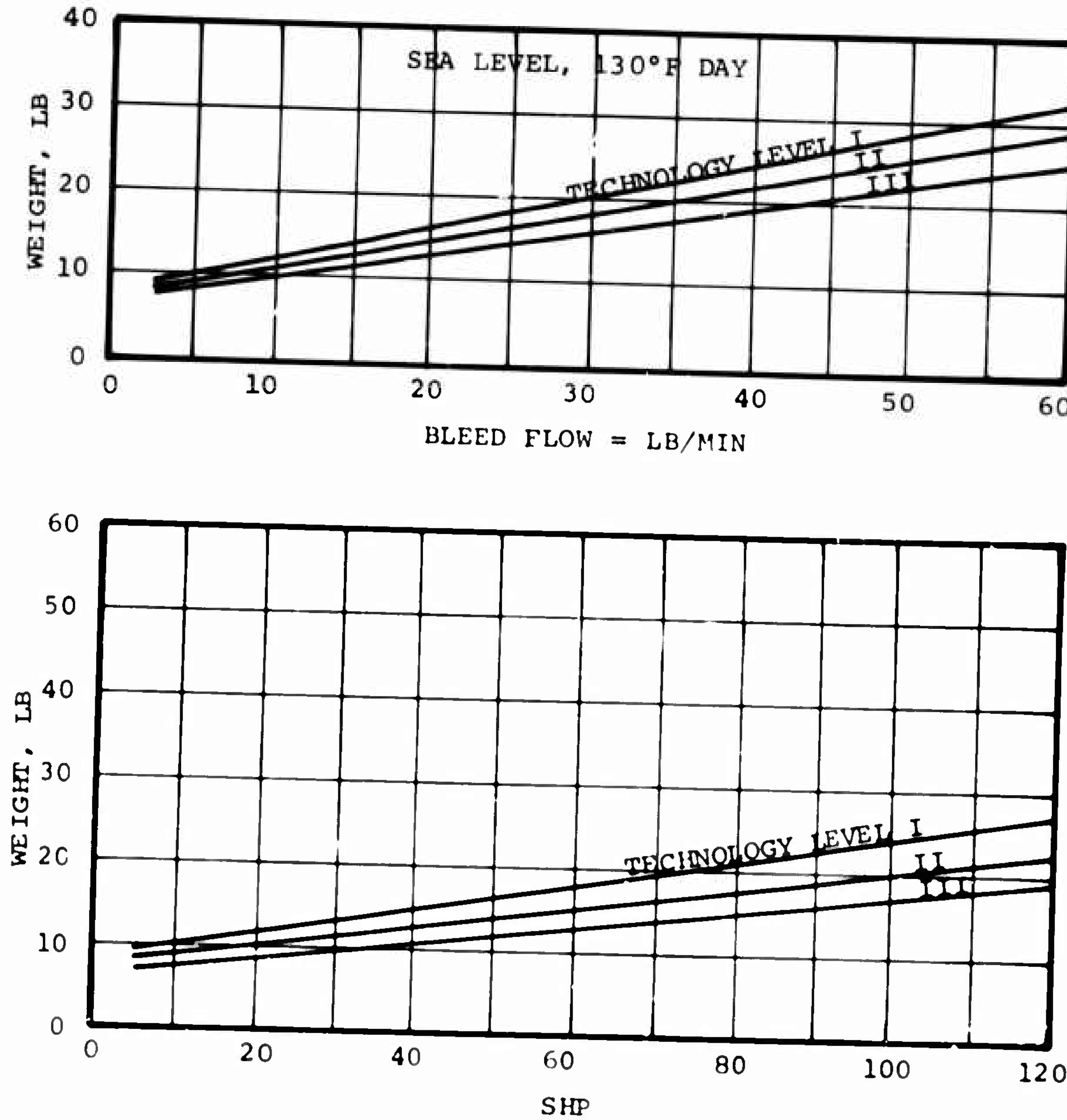


Figure 102. APU Basic Gearbox Weight, Shaft-Power-Only and Bleed-Only APU, Nonregenerated.

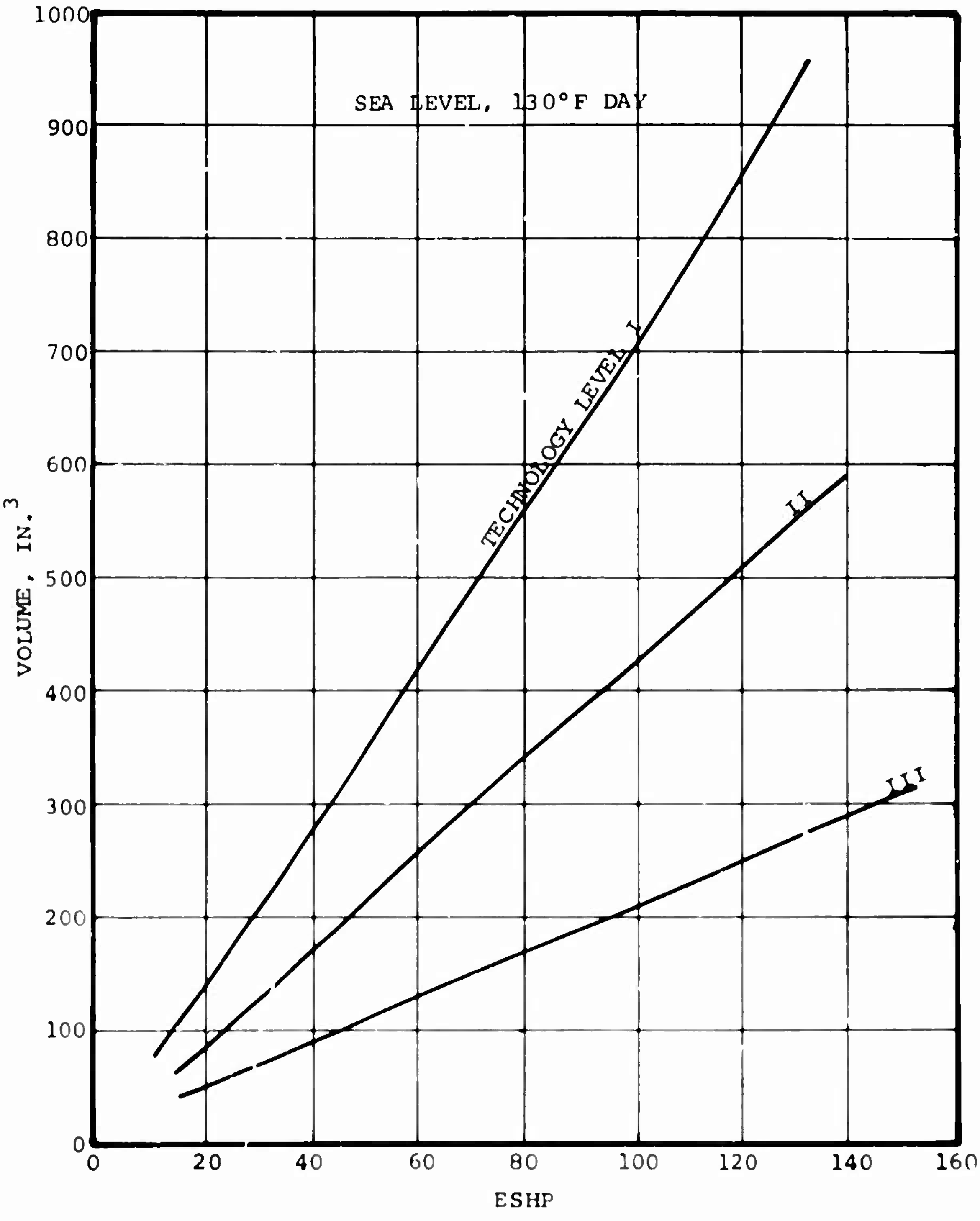


Figure 103. APU Basic Gearbox Volume, Nonregenerated.

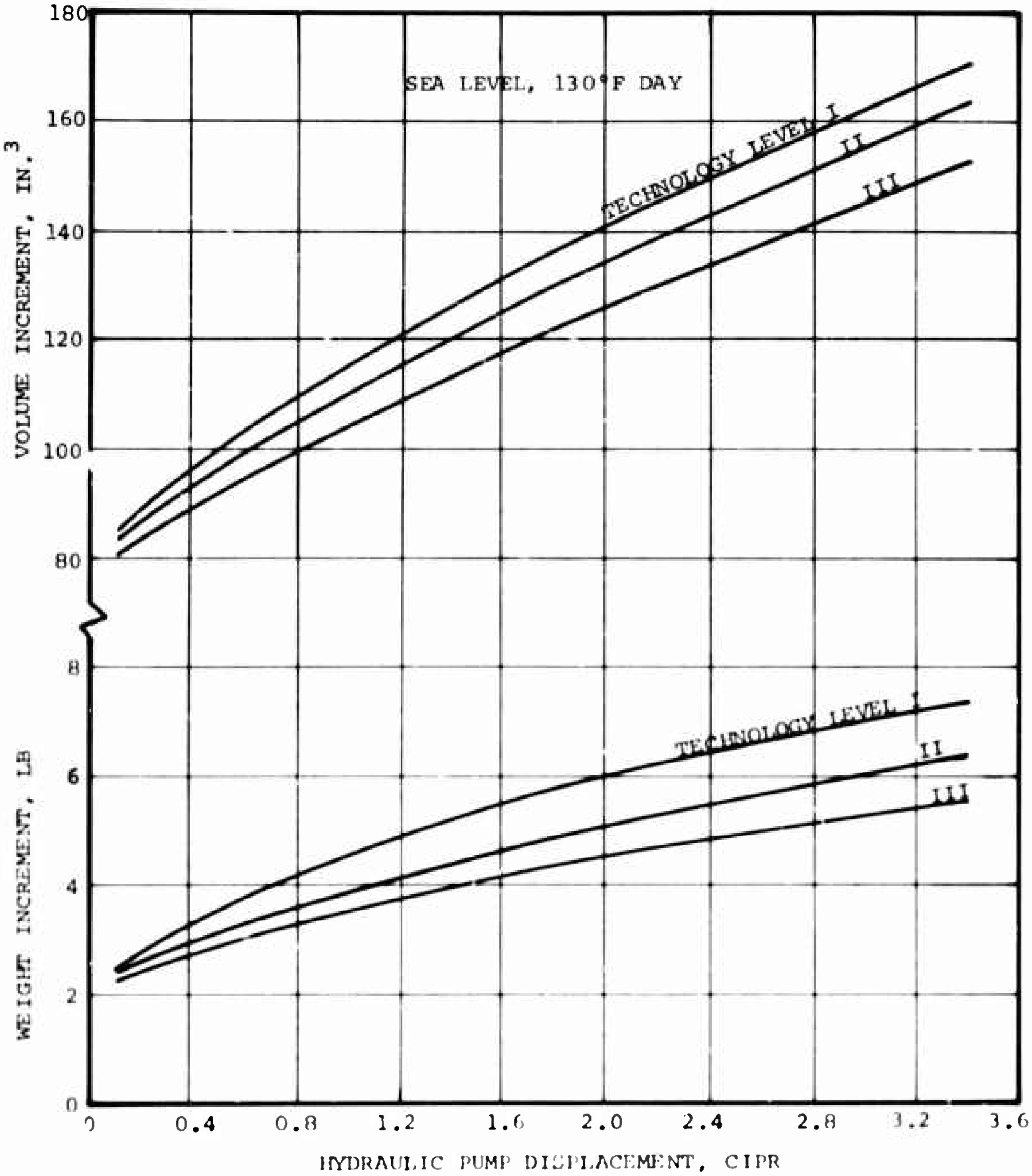


Figure 104. APU Gearbox Weight and Volume Increments for Addition of Hydraulic Pump.

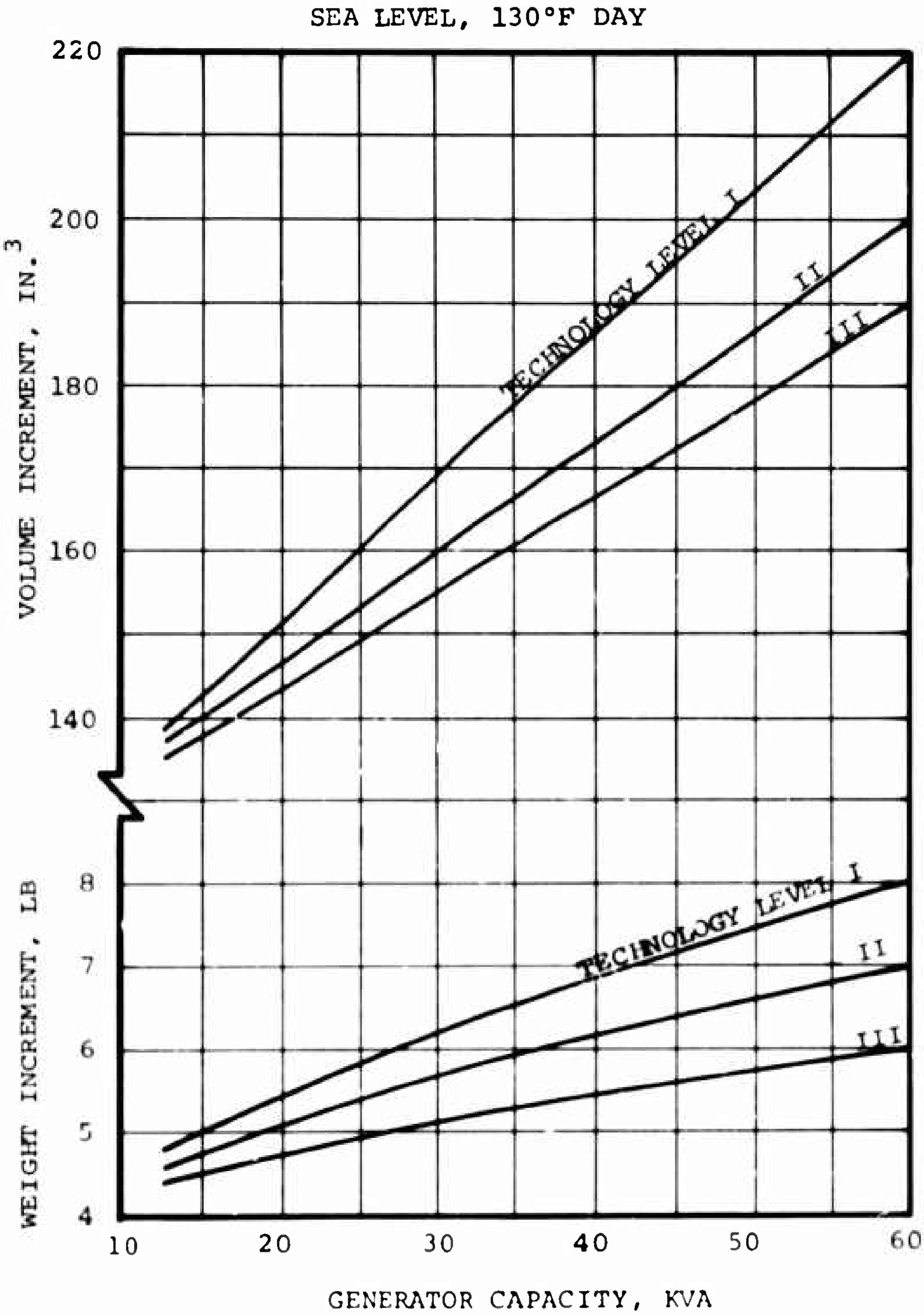


Figure 105. APU Gearbox Weight and Volume Increments for Addition of Generator.

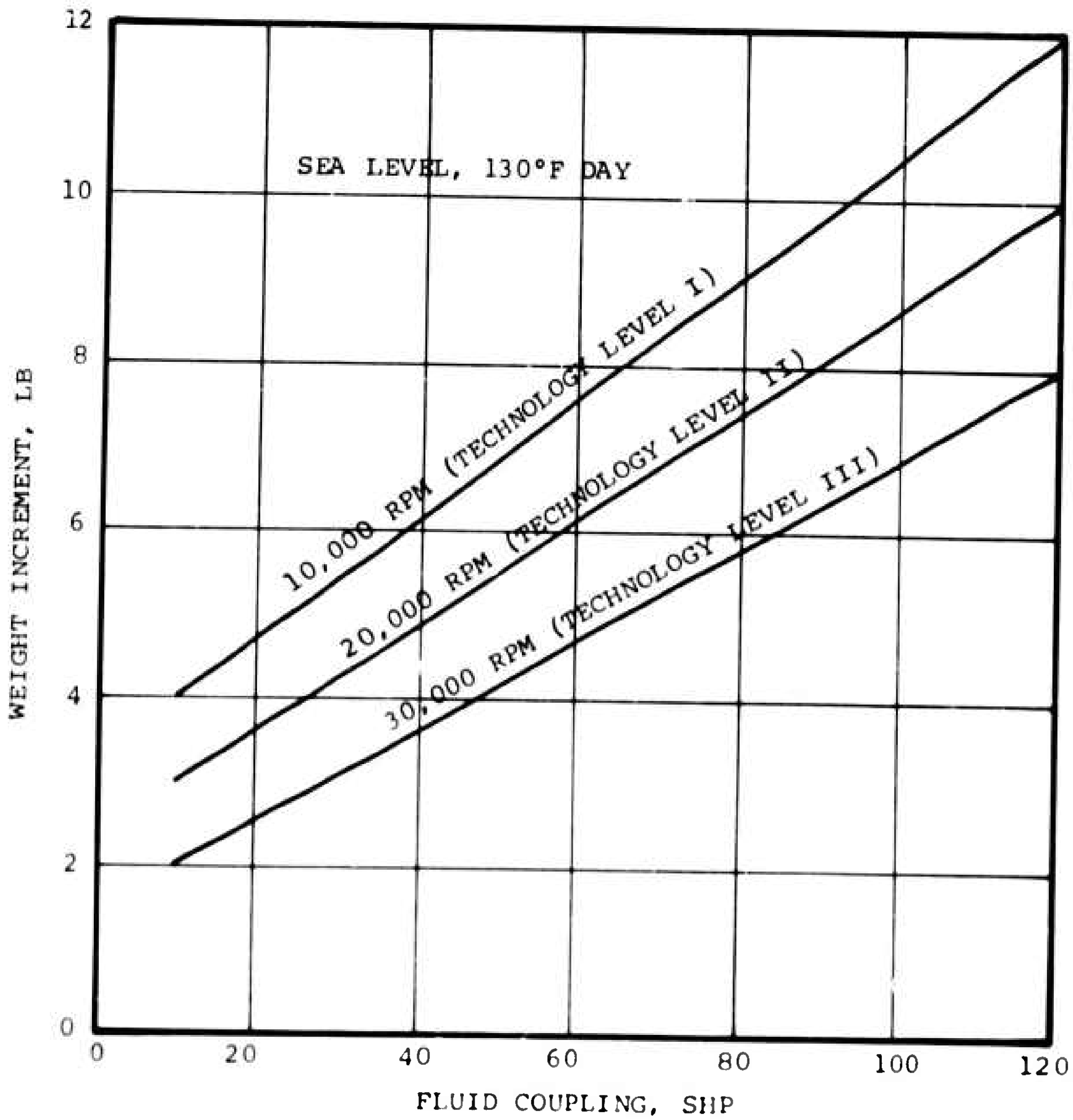


Figure 106. APU Gearbox Weight Increments for Addition of Fluid Coupling.

battery and hydraulic accumulator. The hydraulic accumulator system was selected primarily on the basis of ability to perform at low temperatures with acceptable weight and size penalties to the aircraft. Battery systems, although competitive at higher ambient temperatures, cannot meet the low-temperature requirements without resorting to heating devices. (To obtain satisfactory performance from a battery, the electrolyte temperature should be 0°F or higher.) For this study, the starting system was considered self-sufficient and contained within the aircraft.

A hydraulic system using 3000-psi aircraft supply pressure was sized for each of the various APU's to provide a two-start capability over the extreme ambient temperature range of -65° to 130°F.

For Technology Levels I and II, each system consisted of two accumulators, a hydraulic motor mounted on the APU, a system reservoir, interconnecting lines and system valves, and a small hand pump to provide emergency recharging of the accumulators or topping at extreme low temperatures (Figure 107). The latter feature permitted optimizing the accumulator size without overly penalizing the system for an extreme condition. The system pressure of 3000 psi was increased to 3500 for -65°F. The hydraulic oil conformed to MIL-H-5606.

Systems were optimized by a comprehensive computer program that considered changes in fluid and gas properties, volume, line loss, motor performance, system back pressure, APU performance, and system inertia. System optimization is obtained by varying accumulator volume, gas precharge pressure, initial gas-to-oil fraction, and line size and length. The use of two accumulators for a two-start capability required less total volume than a single two-start accumulator.

The weights and sizes of hydraulic APU starting systems for the APU sizes required by the candidate systems are shown in Figure 108.

The weight and volume curves for Technology Level I and II APU crossed in the lower power rating range. This was the result of an increase in APU operating and self-sustaining speed for Technology Level II, which required a greater oil capacity for the longer cranking period. For Technology Level III and a higher power rating, the trend reversed, since the self-sustaining speed became comparable to Technology Level I or less, and rotor inertia effects were less.

For systems in Technology Level III (Figure 109), a hydraulic intensifier was able to boost the aircraft 3000-psi system

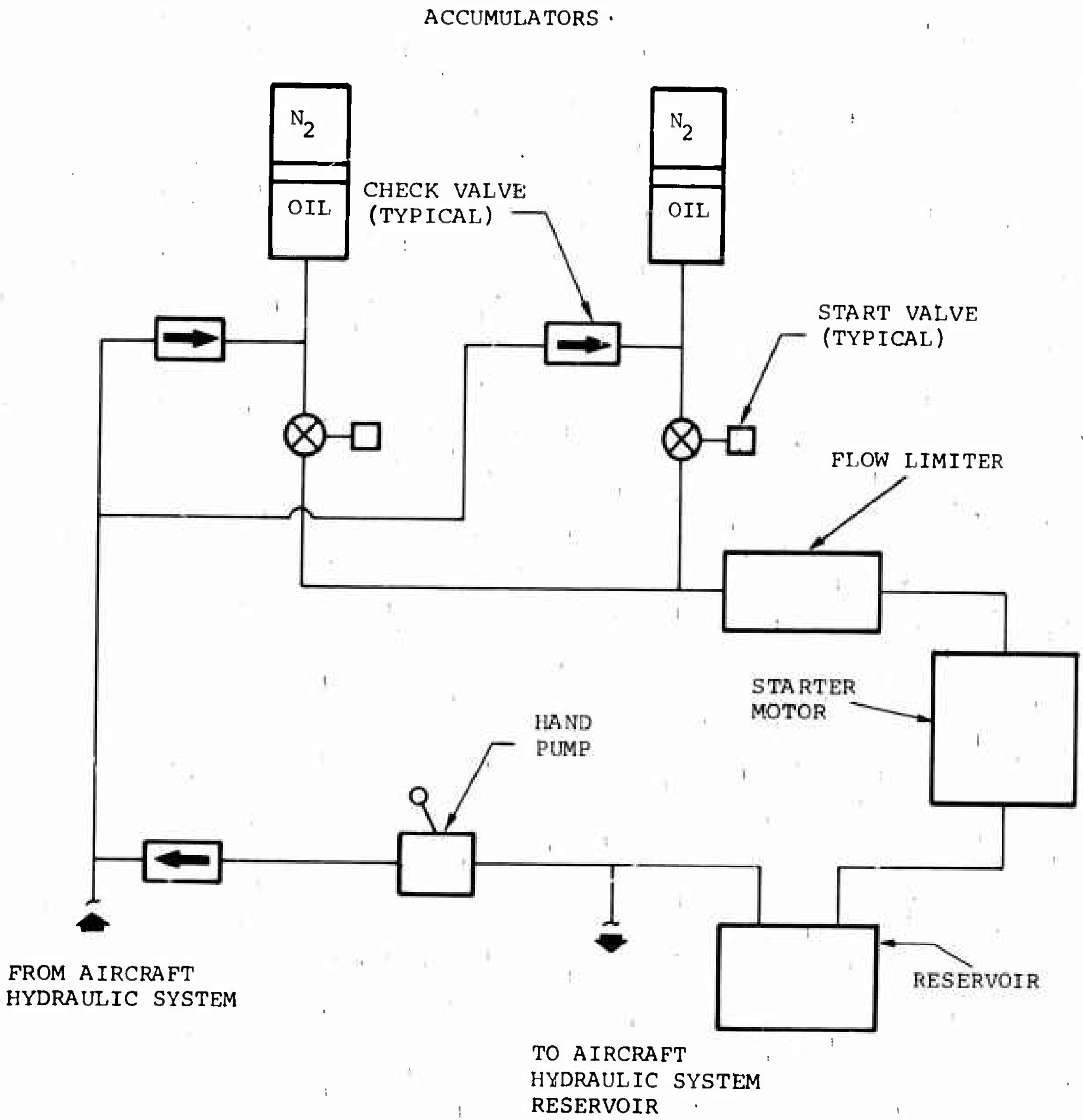


Figure 107. APU Hydraulic Starting System for Technology Levels I and II.

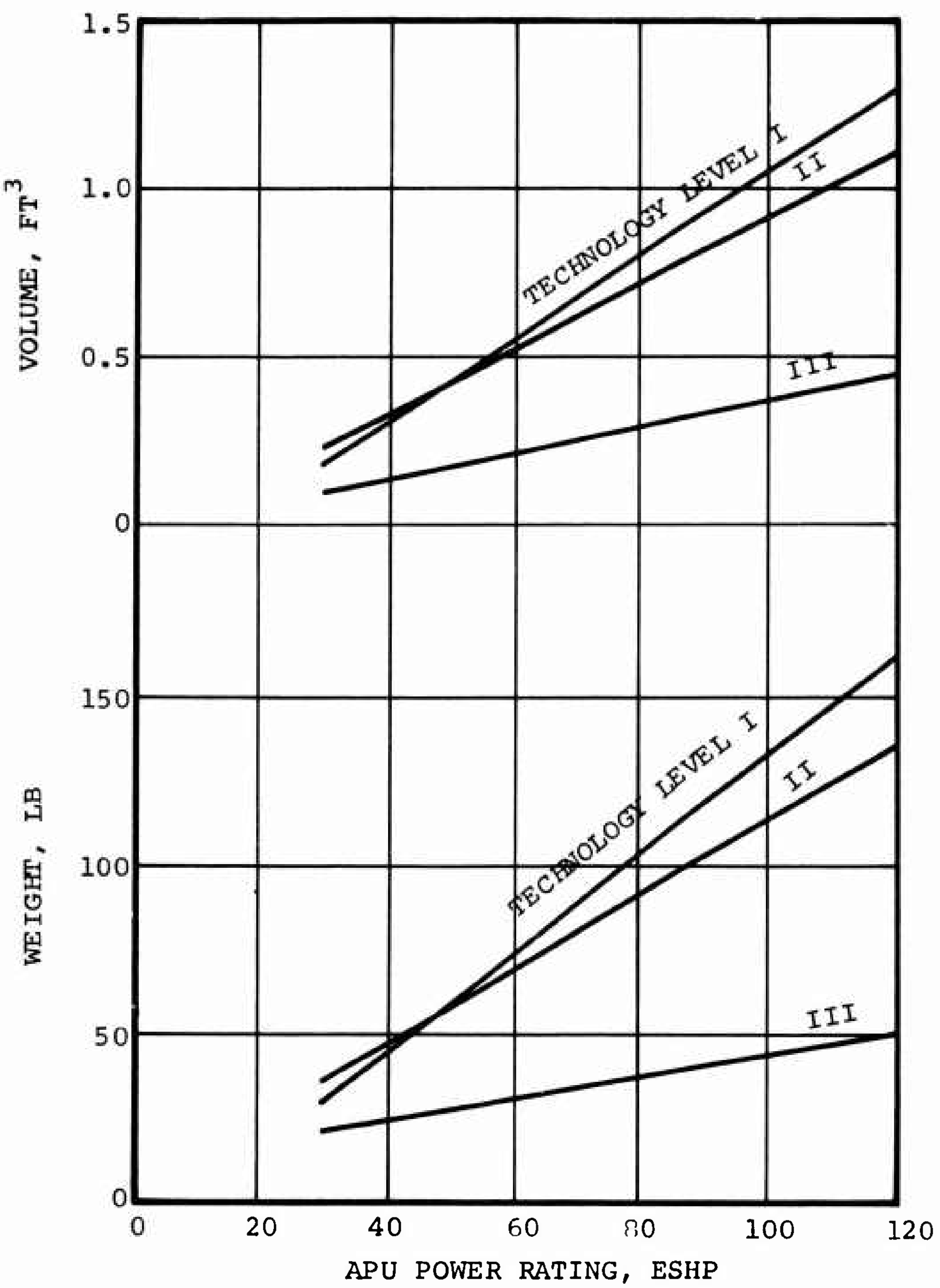


Figure 108. Weight and Vclume of Hydraulic APU Starting System.

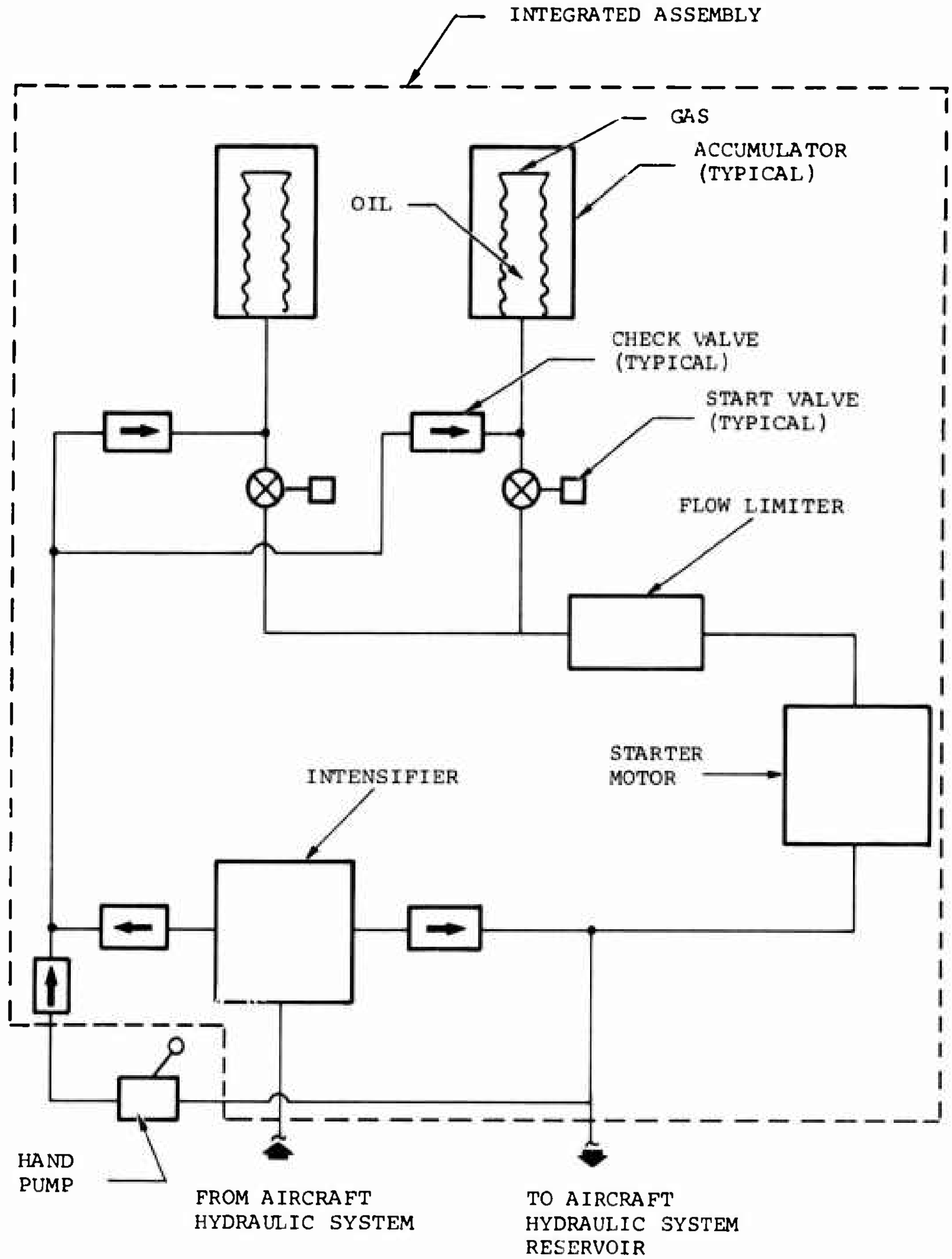


Figure 109. APU Hydraulic Starting System for Technology Level III.

pressure to a higher stored energy level in the accumulator. A pressure of 7500 psi was selected after a preliminary analysis of the 4000- to 10,000-psi range. The intensifier is essentially a hydraulic motor-driven pump that is supplied from the aircraft hydraulic system (Figure 109). The motor and pump are combined in a single housing wherein the pump uses the motor discharge fluid.

The entire hydraulic starting system was assumed to be combined into a single unit, with all parts integrated similar to the primary aircraft hydraulic systems. The estimated weights are significantly lower than conventional lower pressure systems. Lightweight optimized systems components assumed for the Technology Level III analysis are not currently available but are estimated attainable.

The hydraulic APU starting system has the following salient features:

1. Positive two-start capability over the extreme ambient temperature range without the addition of "kit" components

2. Rapid recharging from the aircraft hydraulic system utility pump, after the APU is started

3. Integration with aircraft hydraulic systems, using same fluid and system pressure

4. Provides emergency recharging with hand pump

7. SELECTION OF FINAL CANDIDATE SYSTEMS

The candidate systems defined by Tasks I, II, and III resulted in 27 basic systems that were applicable to all technology levels. The component definitions and power levels in these systems varied sufficiently between technology levels to require analysis of all 27 systems in each level for a total of 81. Inclusion of an air-cycle refrigeration-type ECS required an additional 81 systems for a total of 162 analyzed systems. Redundant main-engine starting systems, if included, would again double the number. The system comparative evaluation further requires establishing 10 evaluation parameters for each system.

To avoid unnecessarily comparing many systems that would definitely be eliminated and to provide a reasonable number of systems for the detailed comparative evaluation, a series of elimination runs of all 162 systems was conducted by using the three evaluation parameters of system weight, system volume, and takeoff gross weight (TOGW) penalty only. Since the combination of these three accounts for 55 percent of the weighted rating in the comparison, an indication was evident of which should be retained as final contenders. As a result of these runs, the six basic systems with the highest ratings were retained as final candidates. Each of these systems was analyzed for the three technology levels, with and without ECS, making a total of 36 systems selected for the complete system comparison for 10 evaluation parameters.

The results of this initial comparative evaluation are summarized in tabular form in Appendix II, where the systems are listed in descending rank. Identification is by a numbering system, as defined in Section 4. The final system candidates are summarized on Tables XXXVIII and XXXIX for systems without and with ECS, respectively.

System 1.4.0.1 was used as reference for the comparative evaluation. The selection was arbitrary, since all systems were compared to the same reference evaluation parameters for each technology level and for systems with and without ECS.

For those without ECS, 1.4.0.1 was the highest ranking system, as indicated by the system merit numbers. This system has a zero rating, since it was the reference. However, all others have a negative number, indicating lower ranking than the reference system. System 1.4.0.1 has an APU separately mounted in the aircraft that directly drives the accessory gearbox by a mechanical link (shaft) between the APU and

TABLE XXXVIII. PRELIMINARY MERIT NUMBER OF FINAL CANDIDATE SYSTEMS WITHOUT ECS

System	Technology Level I	Technology Level II	Technology Level III	Gearbox Link	Engine Start
1.4.0.1	0.000	0.000	0.000	Mechanical	Pneumatic
2.4.0.1	-0.233	-0.089	-0.215	Mechanical	Pneumatic
1.4.1.0	-3.711	-5.372	-2.432	Mechanical	Pneumatic
2.4.1.0	-3.944	-5.477	-2.647	Mechanical	Pneumatic
1.2.0.1	-8.364	-7.463	-5.335	Hydraulic	Pneumatic
1.1.0.1	-9.037	-8.756	-5.727	Pneumatic	Pneumatic

TABLE XXXIX. PRELIMINARY MERIT NUMBER OF FINAL CANDIDATE SYSTEMS WITH ECS

System	Technology Level I	Technology Level II	Technology Level III	Gearbox Link	Engine Start
1.4.0.1	0.000	0.000	0.000	Mechanical	Pneumatic
2.4.0.1	+0.246	+0.906	+0.357	Mechanical	Pneumatic
2.4.1.0	-1.192	-3.075	-1.369	Mechanical	Pneumatic
1.4.1.0	-1.450	-3.398	-1.726	Mechanical	Pneumatic
2.4.2.0	-1.536	-1.476	-2.977	Mechanical	Hydraulic
1.4.2.0	-1.794	-2.294	-3.334	Mechanical	Hydraulic

gearbox for system checkout operation and starts the main engine with a pneumatic engine starting system supplied by bleed-air from the APU.

System 2.4.0.1 is closely ranked with System 1.4.0.1 and is similar, with the APU mounted directly on the accessory gearbox. These two systems appear at the head of the rankings for systems with ECS in reverse order (Table XXXVI).

Two systems, 1.0.0.1 and 1.0.0.2, appear in the upper rankings (Appendix II). These systems have pneumatic and hydraulic main engine starting systems, respectively. Both systems have an electric generator and hydraulic pump mounted on the APU gearbox for system checkout. However, systems of this type do not provide the advantages nor flexibility of those in which the APU supplies power to the accessory gearbox pumps and generator for checkout. Since the complete aircraft system cannot be operated with these and all components that are to be used in flight cannot be checked, these systems were eliminated from the final candidates.

8. SELECTION OF RECOMMENDED SYSTEM

8.1 SYSTEM EVALUATION METHOD

The evaluation method was programmed on a high-speed digital computer to ensure an accurate accounting method and printout for the 36 final candidate systems. The evaluation method is based on assigning one system as the reference, determining the percent improvement or adverse effect (negative improvement) for each of the 10 parameters, weighing these improvements, and adding the results to obtain a total comparative percentage improvement. The comparison parameters and the respective weighting factors are shown on Table XL. The effect of an incremental increase on the improvement is given by the improvement multiplier.

For the reference system, there is no improvement for any of the 10 parameters, and therefore, the sum of the weighted percentile improvements is zero. All other systems will have either a positive or negative comparative index number, denoting a system that is more or less desirable than the reference system, respectively.

The first three evaluation parameters--weight, volume, and TOGW--are calculated. The next three--reliability, maintainability, and availability--are based on calculation and judgment. Vulnerability, aircraft complexity, and SPS complexity are judgmental values that were assigned an arbitrary value of 100 for the reference system. Vulnerability was subdivided into three separate items--volume, complexity, and ruggedness--contributable to the judgmental value. The tenth parameter, life-cycle cost, was calculated and then proportionately reduced so that the reference system value was 100. These evaluation parameters are discussed in detail in the following subsections.

8.2 COMPARISON PARAMETERS

8.2.1 Weight and Volume

The individual component weight, installation factors, and volumes for each system are listed in the upper left corner of the system computer printout data sheets (Appendix I). The installation weight factors, which are multipliers for each component weight, account for additional installation items required to install the component in the aircraft. Some of these additional items--ducts, cables, and valves--are listed among the hydraulic, pneumatic, and electrical system components indicated in the weight columns. The installation factors are lower than those normally associated with the

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TABLE XL. SYSTEM EVALUATION PARAMETERS

Parameter	Improvement Multiplier	Weighting Factor
System Weight	-1	0.10
System Volume	-1	0.05
TOGW Penalty	-1	0.40
Reliability	+1	0.10
Maintainability	-1	0.05
Availability	+1	0.05
Vulnerability	-1	0.02
Aircraft Complexity	-1	0.05
System Complexity	-1	0.05
Life-Cycle Cost	-1	0.13

installation of a single component. These additional system items were shown separately in order to determine the total system volume as closely as possible. The exceptions were the heaters and ECS, which were included as total installed components for convenience in adding or removing them from the systems. The refrigeration package, which is capable of providing either heating or cooling, can be included by removing the separate heater in a system not having refrigeration (with concurrent APU changes) and inserting the refrigeration unit weight, volume, and installation factor.

The APU starting system shown in the component weight list was the hydraulic type utilized in all systems. The starting system size and weight varied according to the APU requirements for each. The hydraulic system was selected as a result of the starting system trade-off studies described in Section 6.7.4.

The heaters in all final candidate systems are bleed-air type, employing a simple ejector to induce and mix ambient air with the APU or main engine bleed-air. An electric motor/fan for

ventilating and a temperature control for regulating bleed airflow were included. All final candidate systems utilize this type heater, since either bleed-air from the APU or compressed air from a secondary gearbox compressor is available during ground operation. Other systems that utilized a combustion-type heater were eliminated in the initial comparisons.

The oil cooling system, including the weights, was a separate item, since it depended upon the cooling requirements of each system. The accessory gearbox was also treated as a separate component. Internally, the gearbox requires a separate lubrication pump to facilitate operation from the APU power source when the main engines are not operating. The lube pump provides oil for all gearbox lubrication and for lubricating and cooling the gearbox-mounted components such as generators, ATM, air compressor, or APU. An air-cooled heat exchanger and electrically driven fan were included in all oil cooling system weights.

The total installation weight of each system in the TOGW analysis is shown on the system data sheets. The system weight and volume used for the first two evaluation parameters are the total of the individual component values in each system.

Weight values comprising the TOGW penalty are indicated on each system data sheet. These are the installed and expendable penalties of the respective aircraft. The expendable weight (fuel burned) is shown by mission segment on each system data sheet. The shaft powers and/or bleed airflows are also indicated. When the APU is the power source, the shaft power is that required at the output of the APU and includes all system losses in producing the mission power. Main engine shaft power is defined as the input to the accessory gearbox from the main transmission.

8.2.2 Takeoff Gross Weight

Takeoff gross weight penalty analysis was conducted on the basis of a constant range and payload, as defined by the aircraft requirements. Therefore, each SPS TOGW determined in the analysis represents the penalty to the aircraft for the same range and payload. By comparing the value of TOGW for a specific SPS to a reference system TOGW, the advantage in system TOGW may be converted to a payload or range advantage. That is, extra fuel and tankage could be added in place of the extra payload to achieve an increase in range.

The influence of the TOGW parameter in the system comparative evaluations is by far the greatest of the 10 parameters, as indicated by the assigned weighting factor of 40 percent. The TOGW is the only parameter which includes system performance and represents the total fixed and expendable weight penalties associated with a complete system in the aircraft during a mission.

The total fixed-weight comprises the total component weight, the weight allowances for mounting, and the associated equipment necessary to install each component in the aircraft and provide power for operation. The total fixed-weight TOGW penalty is then computed by an equipment weight-multiplying factor that accounts for the tankage, structure, and main engine fuel required to transport the SPS through the mission.

The expendable weight consists of all fuel used in extracting power from the APU and main engine for operation of the secondary power system throughout the mission. The weight is computed from the total of all fuel increments in each operating mode and the established APU and engine performance characteristics. The fuel weight is then multiplied by the expendable weight penalty similar to the fixed-weight factor of the fuel, necessary to carry the computed fuel quantity, tankage, and associated aircraft structure allowances. This yields the total mission fuel TOGW penalty as related to the SPS and is added to the total fixed-weight penalty to produce the total fixed and expendable TOGW penalty. The analysis is illustrated in diagram form in Figure 110.

The numerical value thus calculated represents the portion of the total aircraft TOGW attributable to the installation and operation of a candidate system in the aircraft. The penalty factors in the TOGW analysis were previously determined in the survey of the aircraft companies and represent a consensus of these results (Table III).

8.2.3 Maintainability, Availability, and Reliability

A detailed maintainability analysis was conducted for all final candidate systems. Each component was analyzed according to replacement, repair, and/or overhaul requirements within the 5000 flight-hour cycle of the aircraft. A maintainability number for maintenance man-hours per flight-hour (MMH/FH) and mean time to repair (MTTR) was established for each system. A complete analysis summary for the reference system (System 1.4.0.1) is included in Appendix I. The MMH/FH thus obtained was used as the reference maintainability number

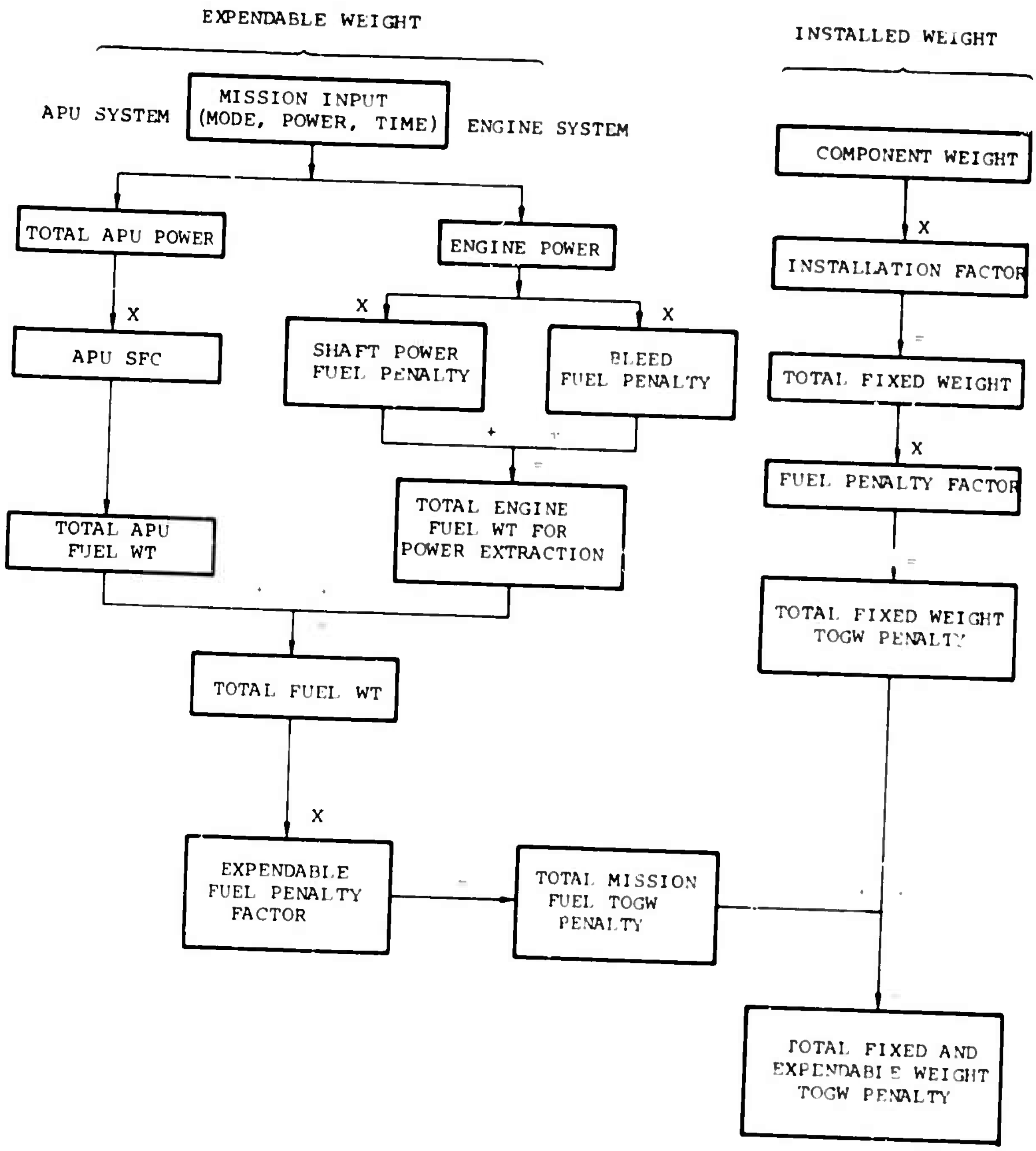

Figure 110. TOGW Penalty Analysis Diagram.

for each system. A maintainability summary for each final candidate system is shown in Tables XLI and XLII for systems without and with ECS, respectively. The component operating cycles and their relationship to flight hours were established from the aircraft mission and power requirements, as shown in Table VII, and from the specified monthly flight-hours in the aircraft PQMR.

The inherent availability of each system is also shown on Tables XLI and XLII. This parameter was calculated by the following formula:

$$A_i = \frac{MTBF}{MTBF + MTTR}$$

where MTBF is the mean time (in aircraft flight hours) between failure as obtained from a reliability analysis. This number represents the percentage of time that the installed system is operable.

The reliability numbers for MTBF are listed on Tables XLI and XLII; these were calculated by analyzing the individual components. A typical failure-frequency analysis is shown in Tables XLIII and XLIV, which show a detailed summary for the reference system 1.4.0.1, without and with ECS for each technology level.

8.2.4 Complexity

The relative complexity of each system is compared to that of the reference system (at a 100-percent value). These results are then used as the bases for further comparison of the system complexity (and its effect) to that of the aircraft.

To determine system complexity, the major system components and subsystems were first separately evaluated by comparing the range of component types appearing in the final candidate systems. This comparison is shown in Table XLV, where the APU, accessory gearbox, APU/gearbox power link system, and engine starting system (with simultaneous electrical power) are listed by various configurations. The least complex was assigned a value of 100 percent and the variations compared to this reference. The APU, for instance, appears in four configurations where the shaft-power-only type was judged as the least complex. The bleed-air-only type, shaft/bleed type, and the shaft/bleed type with an APU-mounted component (in this case, a hydraulic pump) were rated by percent of increase in complexity. Similarly, the other system items were evaluated by their complexity to a reference component or subsystem.

TABLE XLI. SPS RELIABILITY, MAINTAINABILITY, AND AVAILABILITY SUMMARY, WITHOUT ECS

System	Technology Level	MTBF (aircraft hr)	MTTR (hr)	MMH/FH	Availability (A_i) (pct)
1.4.0.1	I	413	3.195	0.088	99.23
	II	491	2.826	0.080	99.42
	III	580	2.873	0.078	99.51
2.4.0.1	I	415	3.288	0.087	99.21
	II	493	2.906	0.079	99.41
	III	590	2.899	0.077	99.52
1.4.1.0	I	392	3.261	0.089	99.13
	II	465	2.941	0.081	99.38
	III	551	2.970	0.079	99.46
2.4.1.0	I	393	3.400	0.090	99.14
	II	466	2.991	0.080	99.36
	III	554	2.999	0.078	99.47
1.2.0.1	I	374	3.650	0.099	99.03
	II	445	3.550	0.097	99.21
	III	525	3.500	0.095	99.34
1.1.0.1	I	382	3.250	0.089	99.16
	II	457	3.150	0.085	99.32
	III	552	3.000	0.080	99.46

TABLE XLII. SPS RELIABILITY, MAINTAINABILITY, AND AVAILABILITY SUMMARY, WITH ECS

System	Technology Level	MTBF (aircraft hr)	MTTR (hr)	MMH/FH	Availability (A_i) (pct)
1.4.0.1	I	361	3.383	0.096	99.06
	II	433	2.907	0.085	99.33
	III	517	2.820	0.081	99.46
2.4.0.1	I	362	3.476	0.095	99.04
	II	435	2.987	0.084	99.31
	III	525	2.846	0.080	99.46
1.4.1.0	I	345	3.449	0.097	99.02
	II	412	3.022	0.086	99.28
	III	494	2.935	0.082	99.40
2.4.1.0	I	346	3.588	0.098	98.97
	II	414	3.072	0.085	99.26
	III	497	2.946	0.081	99.41
1.4.2.0	I	397	3.953	0.105	99.01
	II	466	3.458	0.094	99.26
	III	554	3.414	0.089	99.38
2.4.2.0	I	398	4.043	0.104	98.99
	II	468	3.538	0.093	99.24
	III	556	3.440	0.090	99.39

TABLE XLIII. ESTIMATED FAILURE FREQUENCY PER 1000 FLIGHT HOURS, SYSTEM 1.4.0.1, WITHOUT ECS

Component or Subsystem	Quantity per System	Failures/1000 FH Technology Level I	II	III
Hydraulic Pump Package	2	0.300[a]	0.260[a]	0.240[a]
Electric Generator	2	0.030[b]	0.025[b]	0.020[b]
Electric System Comp				
Generator Unit	2	0.300	0.250	0.236
Transformer-Rectifier	2	0.100	0.090	0.080
Contactors	2	0.060	0.055	0.050
Heater, Bleed Air, Ejector Type	1	0.020	0.016	0.013
Air Turbine Starter, Main Engine	2	0.200	0.160	0.130
ATS Control Valve	2	0.400	0.300	0.250
Fan, Electric Motor Unit	1	0.050	0.040	0.030
Auxiliary Power Unit	1	0.465	0.416	0.333
APU Start System	1	0.093[c]	0.086[c]	0.076[c]
APU Shaft to Gearbox	1	0.007[d]	0.007[d]	0.007[d]
Accessory Gearbox	1	0.300	0.250	0.200
Oil Cooling System	1	0.100	0.080	0.060
System Rate/1000 FH TOTAL		2.425	2.035	1.725
Equivalent System MTBF, FH		413	491	580

[a]Plus scheduled overhaul every 1200, 1500, and 2000 FH.

[b]Plus scheduled overhaul every 5000 FH.

[c]Plus scheduled overhaul every 5350, 5750, and 6500 FH, respectively.

[d]Plus scheduled overhaul every 6000, 10,200, and 15,900 FH, respectively.

TABLE XLIV. ESTIMATED FAILURE FREQUENCY PER 1000 FLIGHT HOURS, SYSTEM 1.4.0.1, WITH ECS

Component or Subsystem	Quantity per System	Failures/1000 FH Technology Level I	II	III
Hydraulic Pump Package	2	0.300[a]	0.260[a]	0.240[a]
Electric Generator	2	0.030[b]	0.025[b]	0.020[b]
Electric System Comp				
Generator Unit	2	0.300	0.250	0.236
Transformer-Rectified	2	0.100	0.090	0.080
Contactors	2	0.060	0.055	0.050
Air Turbine Starter, Main Engine	2	0.200	0.160	0.130
ATS Control Valve	2	0.400	0.300	0.250
Fan, Electric Motor Unit	1	0.050	0.040	0.030
Auxiliary Power Unit	1	0.465	0.416	0.333
APU Start System	1	0.093[c]	0.086[c]	0.076[c]
APU Shaft to Gearbox	1	0.007[d]	0.007[d]	0.007[d]
ECS (Refrigeration Package)	1	0.370[e]	0.287[e]	0.222[e]
Accessory Gearbox	1	0.300	0.250	0.200
Oil Cooling System	1	0.100	0.080	0.060
System Rate/1000 FH TOTAL		2.775	2.306	1.934
Equivalent System MTBF, FH		361	433	517

[a]Plus scheduled overhaul every 1200, 1500, and 2000 FH.

[b]Plus scheduled overhaul every 5000 FH.

[c]Plus scheduled overhaul every 5350, 5750, and 6500 FH, respectively.

[d]Plus scheduled overhaul every 6000, 10,200, and 15,900 FH, respectively.

[e]Plus scheduled overhaul every 1500, 2100, and 3000 FH, respectively.

TABLE XLV. SUBSYSTEM COMPLEXITY FOR FINAL CANDIDATE SYSTEMS

Component or Subsystem	Type	Complexity (pct)	Notes
APU	Shaft power only	100	Simplest configuration and controls
	Bleed air only	108	Addition of bleed and bleed control
	Shaft power/bleed air	110	
	Shaft/bleed with additional APU mounted component	112	Hydraulic pump for hydraulic link to gearbox
Accessory Gearbox	Basic gearbox	100	Reference gearbox: two pump pads and two generator pads
	Add APU shaft input	106	Shaft input flange plus overrunning clutch
	Add hydraulic motor or ATM pad	110	Additional overrunning clutch required
	Add APU mount pad	112	
	Add APU shaft input plus additional component pad	115	Compressor on gearbox with clutch
	Add APU mount pad plus additional component pad	122	Compressor on gearbox with clutch
APU/Gearbox Power Link	APU mounted on gearbox	100	Direct drive from APU to gearbox
	APU shaft input to gearbox	110	Direct drive via shaft
	Pneumatic	115	Bleed APU to ATM on gearbox in System 1.1.0.1
	Hydraulic	120	Hydraulic pump on APU to motor on gearbox in System 1.2.0.1 Hydraulic fluid cooling required
Engine Start System/ Simultaneous Electrical Power from Gearbox Generator	APU bleed/APU on gearbox	100	Most direct power path from APU
	APU bleed/APU gearbox shaft	103	Gearbox drive by shaft
	APU bleed/ATM gearbox drive	108	All pneumatic system
	APU bleed/hydraulic motor gearbox drive	110	Pneumatic start, hydraulic gearbox drive; two-system operation required
	Hydraulic pump on gearbox/ APU on gearbox	112	Direct start pump drive from APU on gearbox; all power through gearbox
	Hydraulic pump on gearbox/ APU-gearbox shaft	115	Utility pump drive from remote APU via shaft; all power through gearbox
	Compressor on gearbox/ APU on gearbox	111	Compressor drive through gearbox; all power through gearbox
	Compressor on gearbox/ APU-gearbox shaft	114	Compressor drive from remote APU via shaft; all power through gearbox

The total system relative complexity was then established by the tailey sheet shown on Table XLVI, where the percent changes in each system component were obtained from the complexity ratings. These individual percents were then totaled to give a system complexity rating. The ratings were then adjusted so that reference System 1.4.0.1 had a rating of 100 percent.

The SPS effect on aircraft complexity was similarly evaluated, with the criteria related to aircraft installation (Tables XLVII and XLVIII).

This evaluation procedure is generally applicable to all technology levels, since improvements or changes in component configurations were applicable to all systems. The APU design, for example, changed considerably with technology level, but the basic design was consistent for a particular level. The ECS does not appear in the relative comparisons, because the inclusion of an ECS in each system was a separate analysis and, therefore, was not a criterion for rejection or acceptance of a given basic system.

8.2.5 Vulnerability

This system comparison parameter is a judgmental factor based on the relativity of one system to the reference system. The vulnerability factor was composed of three parts, with each assigned a weighted value:

Volume	10 pct
Complexity	70
Ruggedness	20
TOTAL	100

The vulnerability parameters in the rating are shown on Table XLIX.

The system volumes, shown on the computer printout sheets in Appendix I were compared by assigning a value of 10 to the reference system (1.4.0.1). The variation in volumes for all final candidate systems was small. Systems with ECS would have a greater volume if directly compared to systems without ECS; however, these two categories were evaluated separately.

System complexity was obtained from the complexity parameter discussed above, with the value changed to 70 for the reference system.

TABLE XLVI. SPS COMPLEXITY FOR FINAL CANDIDATE SYSTEMS

System	APU	Access. Gearbox	APU/Gearbox Power Link	Engine Start System	Total Delta (pct)	Complexity (pct)	Adjusted (pct)
Without ECS							
1.4.0.1	10	6	10	3	29	129	100
2.4.0.1	10	12	0	0	22	122	95
1.4.1.0	0	15	10	14	39	139	108
2.4.1.0	0	22	0	11	33	133	104
1.2.0.1	12	10	20	10	52	152	118
1.1.0.1	8	10	15	8	41	141	109
With ECS							
1.4.0.1	10	6	10	3	29	129	100
2.4.0.1	10	12	0	0	22	122	95
1.4.1.0	0	15	10	15	40	140	109
2.4.1.0	0	22	0	12	34	134	104
1.4.2.0	10	6	10	15	41	141	109
2.4.2.0	10	12	0	12	34	134	104

TABLE XLVII. AIRCRAFT COMPLEXITY FOR SUBSYSTEMS, FINAL CANDIDATE SYSTEMS

Component or Subsystem	Type	Complexity (pct)	Notes
APU	Shaft power only	100	Reference
	Bleed air only	105	Larger APU; bleed valve and duct attachment
	Shaft power/bleed air	106	
	Shaft/Bleed with additional component on APU	107	Hydraulic line connections to APU mounted pump
Accessory Gearbox	Basic gearbox	100	Reference gearbox: two pump pads and two generator pads
	APU shaft input	105	
	Hydraulic motor or ATM pad	106	
	APU mount pad	110	
	APU shaft input plus additional component pad	109	Compressor on gearbox
	APU mount pad plus additional component pad	114	Compressor on gearbox
APU/Gearbox Power Link	APU mounted on gearbox	100	APU mounted directly on gearbox
	APU-gearbox shaft	105	Requires shaft; APU mounted for shaft alignment to gearbox
	Pneumatic	108	Requires ATM on gearbox and single low pressure duct; requires exhaust duct
	Hydraulic	110	Requires pump and motor plus high- and low-pressure lines; requires hydraulic fluid cooling
Engine Start System/ Simultaneous Electrical Power	APU bleed/APU mounted on gearbox	100	Single low-pressure duct from APU to ATS Direct gearbox drive by APU
	APU bleed/APU-gearbox shaft	103	Single low-pressure duct from APU to ATS Direct gearbox drive by APU via shaft
	APU bleed/ATM gearbox drive	105	Single low-pressure duct from APU to ATS Tee off pneumatic system to ATM; all pneumatic system
	APU bleed/Hydraulic motor gearbox drive	108	Single low-pressure duct from APU to ATS Requires hydraulic system operation
	Hydraulic pump on gearbox/ APU on gearbox	105	High- and low-pressure lines from pump to starter Direct gearbox drive by APU
	Hydraulic pump on gearbox/ APU-gearbox shaft	108	High- and low-pressure lines from pump to starter Gearbox drive via shaft
	Compressor on gearbox/APU on gearbox	107	Single pneumatic duct from compressor to ATS Direct gearbox drive; compressor inlet duct
	Compressor on gearbox/APU-gearbox shaft	110	Single pneumatic duct from compressor to ATS Gearbox drive via shaft; compressor inlet duct

TABLE XLVIII. AIRCRAFT COMPLEXITY FOR SPS FINAL CANDIDATE SYSTEMS

System	APU	Access. Gearbox	APU/Gearbox Power Link	Engine Start System	Total Delta (pct)	Complexity (pct)	Adjusted (pct)
Without ECS							
1.4.0.1	6	5	5	3	19	[illegible]	100
2.4.0.1	6	10	0	0	16	[illegible]	98
1.4.1.0	0	9	5	10	24	124	104
2.4.1.0	0	14	0	7	21	121	102
1.2.0.1	7	6	10	8	31	131	110
1.1.0.1	5	6	8	5	24	124	104
With ECS							
1.4.0.1	6	5	5	3	19	119	100
2.4.0.1	6	10	0	0	16	116	98
1.4.1.0	0	9	5	10	24	124	104
2.4.1.0	0	14	0	7	21	121	102
1.4.2.0	6	5	5	8	24	124	104
2.4.2.0	6	10	0	5	21	121	102

TABLE XLIX. SPS VULNERABILITY COMPARISON FINAL CANDIDATE SYSTEMS

System	Volume (pct)	Complexity (pct)	Ruggedness (pct)	Total (pct)
Without ECS				
1.4.0.1	10.0	70	20	100
2.4.0.1	10.1	67	19	96
1.4.1.0	10.4	76	21	107
2.4.1.0	10.5	73	20	103
1.2.0.1	11.3	83	24	118
1.1.0.1	11.5	76	20	108
With ECS				
1.4.0.1	10.0	70	20	100
2.4.0.1	9.95	67	19	96
1.4.1.0	9.95	76	21	107
2.4.1.0	9.9	73	20	103
1.4.2.0	10.2	76	24	110
2.4.2.0	10.1	73	23	106

The ruggedness was determined by separately evaluating the major system components and subsystems. These are listed on Table L, where each was subdivided into the types appearing in the final candidate systems. A value of 100 percent was assigned to the type judged with the highest degree of ruggedness; other items received a lesser percent.

The delta percents (negative) were then listed for each component or subsystem in each candidate system (Table LI), and the absolute percent rating was established. A final adjusted percent-rating was established by inverting these absolute ratings and using 20 as the base for the reference system. The inversion was necessary to obtain the proper effect on the system vulnerability, since the less rugged systems were considered more vulnerable.

8.2.6 Life-Cycle Cost

The life-cycle cost for each final candidate system was computed on the basis of the initial cost plus overhaul, repair parts costs, and labor for each item in the system. All costs were based on a 5000-hr airframe life and maintainability costs consistent with that data. All costs are shown in percent, relative to the reference system for each technology level. Separate reference values were used for systems with and without ECS.

8.3 RESULTS OF SYSTEM COMPARATIVE EVALUATION

8.3.1 Recommended System

The results of the comparative evaluations of the final candidate systems are shown in the computer printout sheets in Appendix I. Table LII lists the system merit numbers (weighted percent improvement). This table shows that System 2.4.0.1 consistently received the highest ranking in all technology levels both with and without ECS and is, therefore, the recommended system.

Figure 111 shows the recommended system schematic, and the APU-gearbox configuration outline envisioned for Technology Level II is shown in Figure 112. The air turbine starter for this system and the optional ECS package outline are shown in Figures 113 and 114, respectively.

The reference system, 1.4.0.1, is quite close in ranking to System 2.4.0.1 and is similar, with the APU separately mounted by a shaft connection to the gearbox. The relationship of these two systems was consistent for all technology levels with and without ECS. The actual choice will be by

TABLE L. SPS SUBSYSTEM RUGGEDNESS COMPARISON, FINAL CANDIDATE SYSTEMS

Component or Subsystem	Type	Ruggedness (pct)	Notes
APU	Shaft power only	100	Most compact design; single type of power
	Bleed air only	95	Bleed valve and controls added; single type of power Less gearbox required
	Shaft power/bleed air	93	Two types of power
	Shaft/bleed with additional APU mounted component	91	Two types of power; additional APU gearbox pad plus hydraulic pump
Accessory Gearbox	Basic gearbox	100	Simplest type reference - not included in final candidate system
	Add APU shaft input	98	Addition of input shaft flange
	Add hydraulic motor or ATM pad	95	Addition of component pad and overrunning clutch
	Add APU mount pad	95	APU supported from mount pad
	Add APU shaft input plus additional component pad	93	
	Add APU mount pad plus additional component pad	91	
APU/Gearbox Power Link	APU mounted on gearbox	100	Gear linkage in gearbox
	APU shaft input to gearbox	95	Shaft addition increases linkage damage probability
	Pneumatic	97	Pneumatic duct ability to sustain limited operation with leakage
	Hydraulic	90	Hydraulic system susceptible to fluid depletion from damage
Engine Start System/ Simultaneous Electrical Power from Gearbox	Pneumatic-APU bleed/mechanical link - APU on box	100	Pneumatic duct ability to sustain limited operation with leakage from damage
	Pneumatic-APU bleed/mechanical link - shaft	98	Pneumatic duct ability to sustain limited operation with leakage from damage
	Pneumatic-APU bleed/pneumatic link - ATM on box	96	All pneumatic system
	Pneumatic-APU bleed/hydraulic link - motor on box	92	Pneumatic and hydraulic system operation required
	Pneumatic-Compressor/Mechanical link - APU on box	94	Pneumatic start system with compressor added to gearbox
	Pneumatic-compressor/mechanical link - shaft	92	Pneumatic start system with compressor added to gearbox
	Hydraulic/mechanical link - APU on box	87	Hydraulic system susceptible to leakage and fluid depletion from damage
	Hydraulic/mechanical link - shaft	85	Hydraulic system susceptible to leakage and fluid depletion from damage

TABLE LI. SPS RUGGEDNESS COMPARISON, FINAL CANDIDATE SYSTEMS

System	APU	Access. Gearbox	APU/Gearbox Power Link	Engine Start System	Total Delta (pct)	Complexity (pct)	Adjusted (pct)
Without ECS							
1.4.0.1	-7	-2	-5	-2	-16	84	20
2.4.0.1	-7	-5	0	0	-12	88	19
1.4.1.0	0	-7	-5	-8	-20	80	21
2.4.1.0	0	-9	0	-6	-15	85	20
1.2.0.1	-9	-5	-10	-8	-32	68	24
1.1.0.1	-5	-5	-3	-4	-17	83	20
With ECS							
1.4.0.1	-7	-2	-5	-2	-16	84	20
2.4.0.1	-7	-5	0	0	-12	88	19
1.4.1.0	0	-7	-5	-8	-20	80	21
2.4.1.0	0	-9	0	-6	-15	85	20
1.4.2.0	-7	-7	-5	-15	-34	66	24
2.4.2.0	-7	-9	0	-13	-29	71	23

TABLE LII. COMP
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	Technology Level I					
Evaluation Parameters	1.1.0.1	1.2.0.1	1.4.1.0	2.4.1.0	1.4.0.1	2.4.0
System Weight	-1.685	-1.640	-0.820	-0.848	0	-0.0
System Volume	-0.771	-0.632	-0.227	-0.277	0	-0.0
TOGW Penalty	-6.581	-6.091	-2.663	-2.356	0	-0.1
Reliability (MTBF)	-0.770	-0.970	-0.530	-0.510	0	0.0
Maintainability (MMH/FH)	-0.057	-0.625	-0.057	-0.114	0	0.0
Availability	-0.004	-0.010	-0.005	-0.005	0	-0.0
System Vulnerability	-0.160	-0.360	-0.140	-0.060	0	0.0
Aircraft Complexity	-0.200	-0.500	-0.200	-0.100	0	0.1
SPS Complexity	-0.450	-0.900	-0.400	-0.200	0	0.2
Life-Cycle Cost	-3.251	-1.360	-2.601	-2.426	0	-0.0
SPS Total Weighted Percent Improvement	-13.931	-13.085	-7.645	-6.892	0.000	0.2

Evaluation Parameters	1.4.1.0	2.4.1.0	1.4.2.0	2.4.2.0	1.4.0.1	2.4.0
System Weight	-0.544	-0.478	-0.441	-0.375	0	0.06
System Volume	0.026	0.058	-0.090	-0.058	0	0.03
TOGW Penalty	-0.933	-0.773	-1.263	-1.103	0	0.15
Reliability (MTBF)	-0.440	-0.420	1.000	1.02	0	0.03
Maintainability (MMH/FH)	-0.052	-0.104	-0.469	-0.417	0	0.05
Availability	-0.002	-0.005	-0.003	-0.004	0	-0.00
System Vulnerability	-0.140	-0.060	-0.200	-0.120	0	0.08
Aircraft Complexity	-0.200	-0.100	-0.200	-0.100	0	0.10
SPS Complexity	-0.450	-0.200	-0.450	-0.200	0	0.25
Life-Cycle Cost	-2.473	-2.298	-0.393	-0.448	0	-0.05
SPS Total Weighted Percent Improvement	-5.210 -3.350*	-4.375 -2.275*	-2.510	-1.799	0.000	0.69

*ECS furnished compressed air from load compressors on gearbox rather than bleed ai

BLE LII. COMPARATIVE EVALUATION OF FINAL CANDIDATE SYSTEMS
(Weighted Percent Improvement)

		Technology Level II							
		Systems Without ECS							
.4.0.1	2.4.0.1	1.1.0.1	1.2.0.1	1.4.1.0	2.4.1.0	1.4.0.1	2.4.0.1	1.1.0.1	1.2.0.
0	-0.028	-1.634	-1.488	-1.081	-1.081	0	0.003	-1.109	-1.08
0	-0.049	-0.678	-0.503	-0.350	-0.405	0	-0.055	-0.221	-0.33
0	-0.155	-6.444	-5.472	-3.941	-3.992	0	-0.037	-4.398	-3.91
0	0.020	-0.690	-0.940	-0.530	-0.510	0	0.040	-0.580	-1.04
0	0.057	-0.312	-1.062	-0.062	0.000	0	0.062	-01.28	-1.04
0	-0.001	-0.005	-0.011	-0.002	-0.003	0	-0.001	-0.003	-0.00
0	0.080	-0.160	-0.360	-0.140	-0.060	0	0.080	-0.160	-0.36
0	0.100	-0.200	-0.500	-0.200	-0.100	0	0.100	-0.200	-0.50
0	0.250	-0.450	-0.900	-0.400	-0.200	0	0.250	-0.450	-0.90
0	-0.060	-3.110	-1.334	-2.436	-2.257	0	-0.078	-2.938	-1.20
0.000	0.217	-13.686	-12.567	-9.142	-8.606	0.000	0.366	-10.186	-10.44
		Systems With ECS							
.0.1	2.4.0.1	1.4.1.0	2.4.1.0	1.4.2.0	2.4.2.0	1.4.0.1	2.4.0.1	1.4.1.0	2.4.1.
0	0.064	-0.823	-0.744	-0.545	-0.382	0	0.185	-0.506	-0.422
0	0.032	-0.207	-0.164	-0.181	-0.086	0	0.069	-0.285	-0.230
0	0.150	-2.368	-2.167	-1.567	-1.008	0	0.653	-0.935	-0.718
0	0.030	-0.480	-0.440	0.760	0.810	0	0.050	-0.570	-0.520
0	0.052	-0.059	0.000	-0.529	-0.471	0	0.059	-0.062	0.000
0	-0.001	-0.003	-0.004	-0.004	-0.005	0	-0.001	-0.003	-0.003
0	0.080	-0.140	-0.060	-0.200	-0.120	0	0.080	-0.140	-0.060
0	0.100	-0.200	-0.100	-0.200	-0.100	0	0.100	-0.200	-0.100
0	0.250	-0.450	-0.200	-0.450	-0.200	0	0.250	-0.450	-0.200
0	-0.056	-2.307	-2.137	-0.218	-0.292	0	-0.074	-2.236	-2.067
.000	0.699	-7.042 -3.440*	-6.014 -3.671*	-3.133	-1.855	0.000	1.366	-5.389 -3.484*	-4.314 -2.777

than bleed air from main engines in flight.

		Technology Level III					
.0.1	2.4.0.1	1.1.0.1	1.2.0.1	1.4.1.0	2.4.1.0	1.4.0.1	2.4.0.1
0	0.003	-1.109	-1.087	-0.609	-0.628	0	-0.019
0	-0.055	-0.221	-0.338	-0.312	-0.377	0	-0.065
0	-0.037	-4.398	-3.910	-1.511	-1.643	0	-0.131
0	0.040	-0.580	-1.040	-0.600	-0.550	0	0.070
0	0.062	-01.28	-1.040	-0.064	0.000	0	0.064
0	-0.001	-0.003	-0.009	-0.003	-0.002	0	0.001
0	0.080	-0.160	-0.360	-0.140	-0.060	0	0.080
0	0.100	-0.200	-0.500	-0.200	-0.100	0	0.100
0	0.250	-0.450	-0.900	-0.400	-0.200	0	0.250
0	-0.078	-2.938	-1.208	-2.361	-2.181	0	-0.051
000	0.366	-10.186	-10.442	-6.197	-5.737	0.000	0.297

.0.1	2.4.0.1	1.4.1.0	2.4.1.0	1.4.2.0	2.4.2.0	1.4.0.1	2.4.0.1
0	0.185	-0.506	-0.422	-0.799	-0.714	0	0.085
0	0.069	-0.285	-0.230	-0.252	-0.197	0	0.055
0	0.653	-0.935	-0.718	-2.283	-2.066	0	0.217
0	0.050	-0.570	-0.520	0.570	0.610	0	0.020
0	0.059	-0.062	0.000	-0.494	-0.556	0	0.062
0	-0.001	-0.003	-0.003	-0.004	-0.004	0	0.000
0	0.080	-0.140	-0.060	-0.200	-0.120	0	0.080
0	0.100	-0.200	-0.100	-0.200	-0.100	0	0.100
0	0.250	-0.450	-0.200	-0.450	-0.200	0	0.250
0	-0.074	-2.236	-2.067	0.186	0.137	0	-0.048
000	1.366	-5.389 -3.484*	-4.314 -2.777*	-3.923	-3.209	0.000	0.819

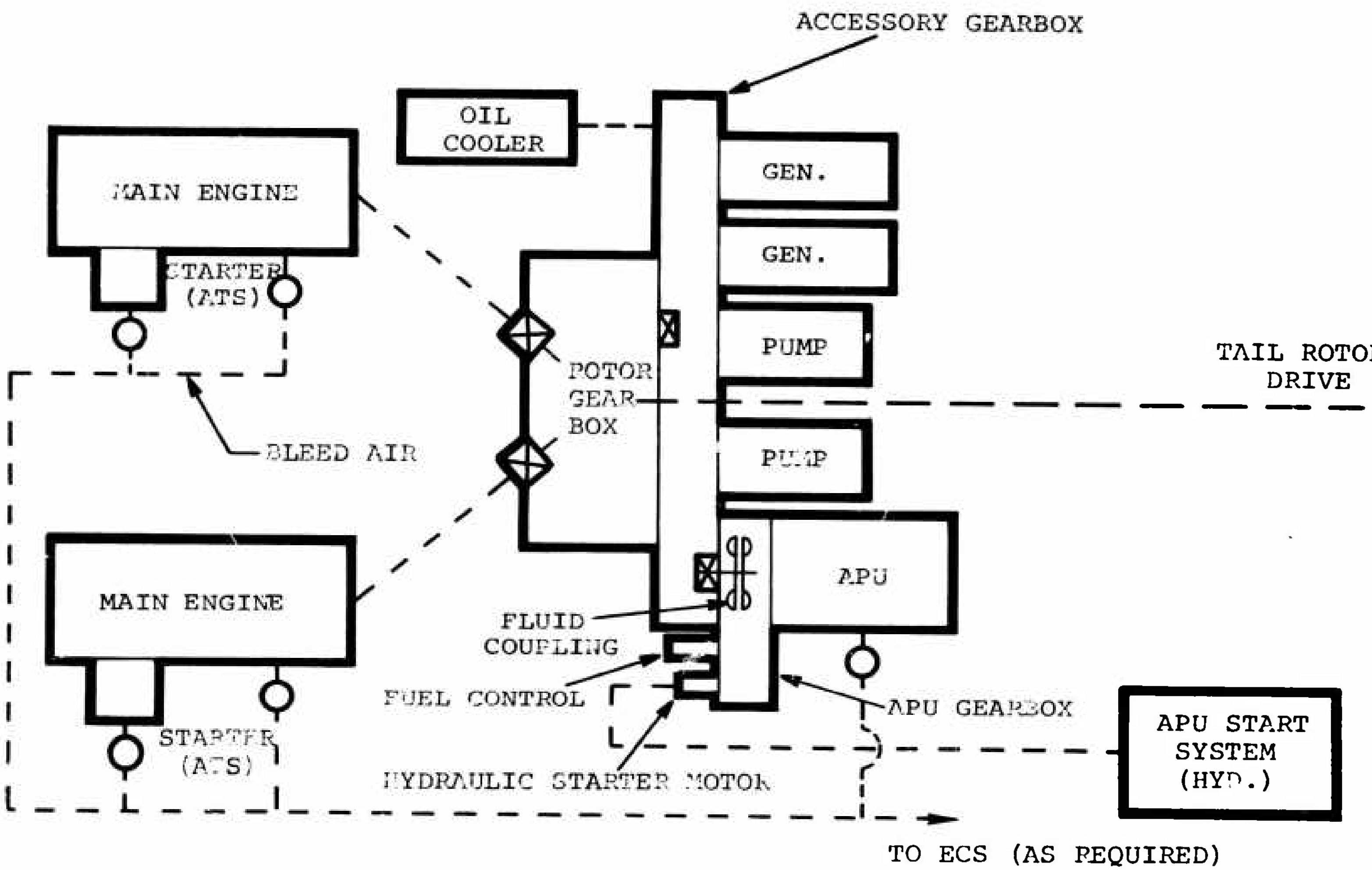

Figure 111. Recommended System Schematic.

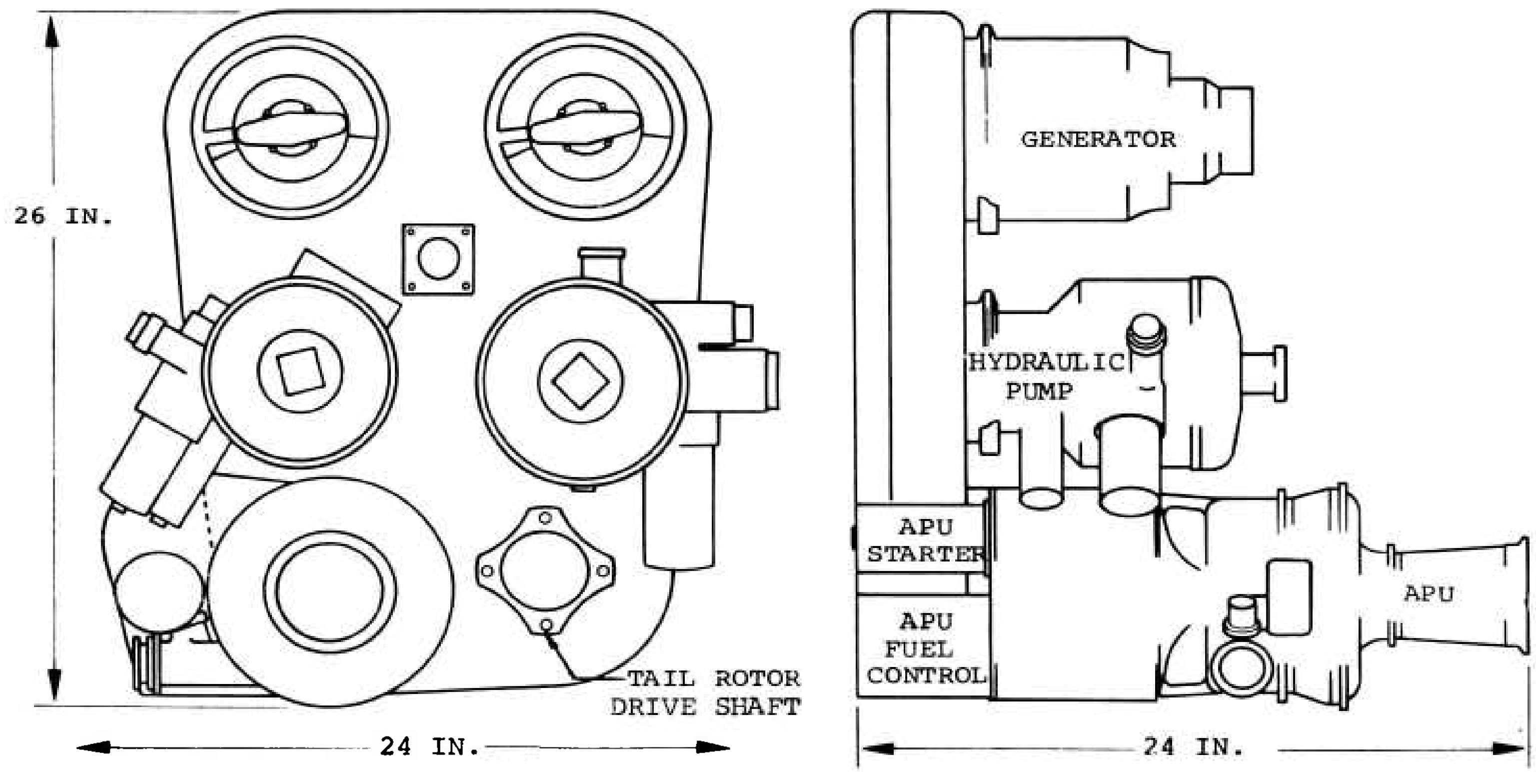

Figure 112. Recommended System Outline.

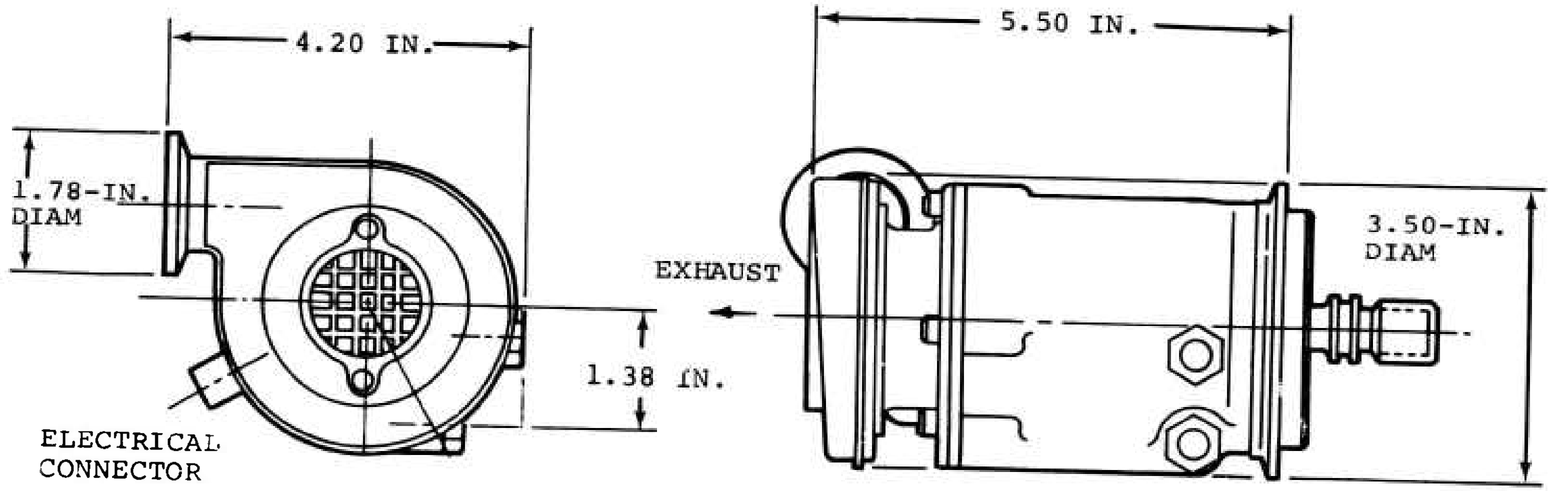

Figure 113. Advanced Air Turbine Starter for Recommended System.

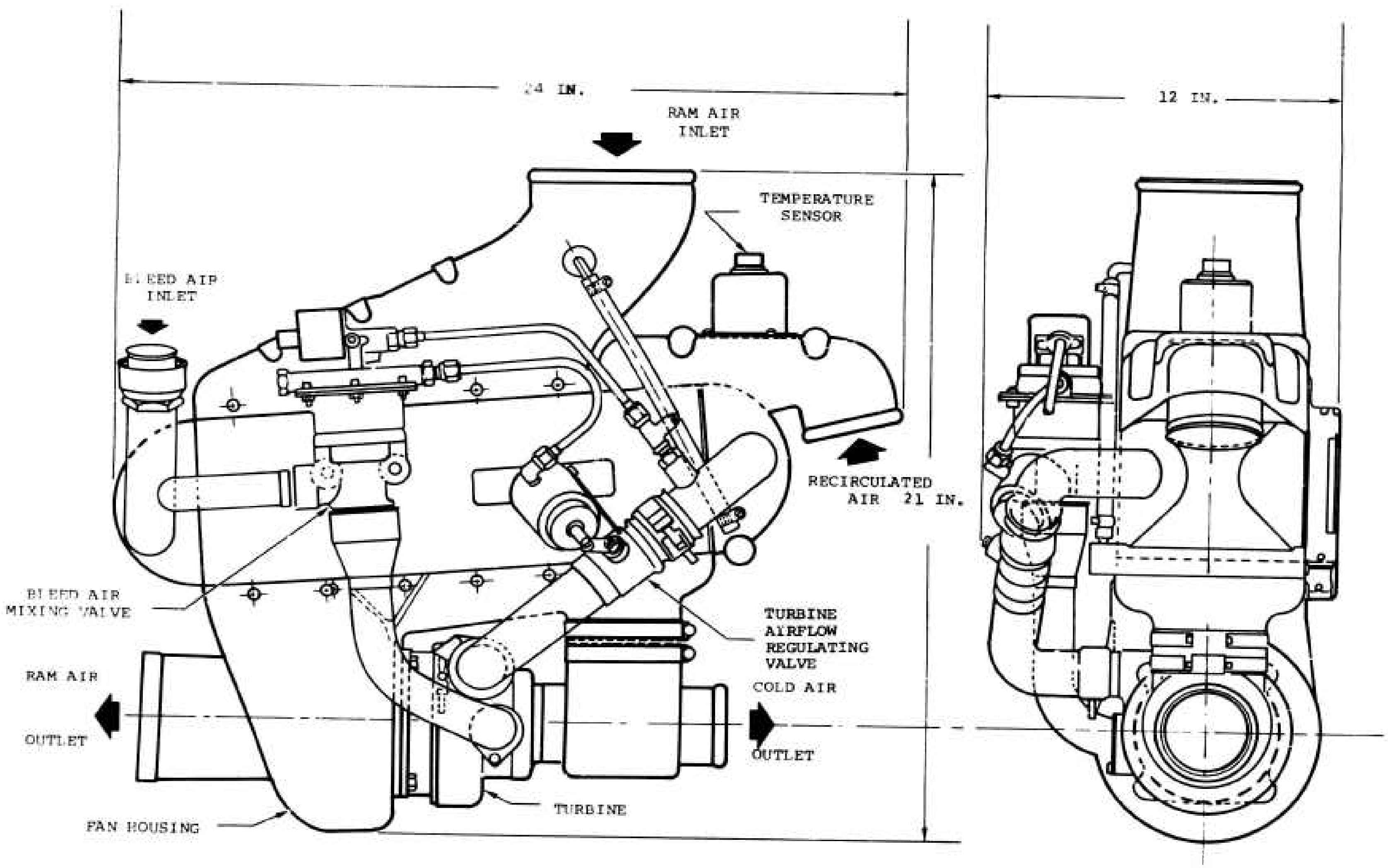

Figure 114. Air Cycle ECS Package.

installation considerations, such as APU operating environment or available space.

The recommended system consists of two electrical (redundant) generators, a flight control hydraulic pump, a utility (and redundant flight control) pump, and an APU mounted on an accessory gearbox. System components mounted elsewhere in the aircraft include a hydraulic APU starting system, an air turbine starter on each engine, and an environmental control system (optional). The accessory gearbox is driven by the main engines in flight from the main rotor transmission. For ground operation (or emergency in flight), the APU drives the accessory gearbox. An overrunning, or one-way device, is included to prevent the rotor gearbox from being driven by the APU. Another is located at the APU input to the gearbox to prevent the fluid coupling elements from being driven when the main engines are operating the accessory gearbox. In this schematic, the accessory gearbox is driven from the tail rotor drive. This method was shown as an example, and a separate shaft could have been used. Additional system redundancy may be obtained from small pumps and/or an electric generator mounted on the rotor transmission.

With the APU operating, electric or hydraulic power is available from the accessory gearbox for systems checkout or maintenance, and bleed-air is available for pneumatic engine starting the main engines or for the ECS. Heat for the cockpit and cabin is also available, by using APU bleed-air in conjunction with the bleed-air heater.

The APU is a bleed-air/shaft-power type (single shaft) mounted directly on the accessory gearbox as a separate and replaceable component. The fluid coupling included in the gearbox is a fill-and-drain unit through which power is transmitted to the accessories. Although less efficient than a clutch, the fluid coupling is inherently more reliable. The capability of disconnecting the gearbox and accessory drag for APU starting allows the APU size to be optimized. The coupling may be filled after the APU is started by opening a solenoid valve in the gearbox lube system from the cockpit or another remote-control panel. Since the oil flow is continuous, draining is automatic and rapidly accomplished through centrifugal force action on the oil, when the oil supply is shut off. An overrunning device may be included at the fluid coupling output shaft to prevent driving these elements, as the gearbox is driven by the main engines.

The air turbine starters are connected to the APU bleed by a duct to allow selection of either starting system. The starting system would usually be connected to the main engine bleed duct system to allow cross-bleed engine starts in flight.

8.3.2 Systems Comparison

Without ECS, the third and fourth ranked systems (1.4.1.0 and 2.4.1.0) fall within a narrow range of approximately 6 to 9 percent below the first-ranked system, depending upon technology level. These systems use a compressor mounted on the accessory gearbox, a pneumatic engine starting system, and a shaft-power APU. Systems 1.2.0.1 and 1.1.0.1 are ranked fifth and sixth in a percentage range of approximately 10 to 14 percent.

With ECS, the third, fourth, fifth, and sixth ranked systems are within a rather narrow range from 2.5 to 5 percent above System 2.4.0.1. Systems 2.4.2.0 and 1.4.2.0, which employ a hydraulic main engine starting system, have a slight edge of about 0.5 to 1.8 percentage points over Systems 2.4.1.0 and 1.4.1.0 in the first two technology levels. However, this trend reverses in the most advanced technology level where both systems shows a slight advantage. Two ratings for each of these latter systems are shown on Table LII, indicating the effect of driving the gearbox-mounted air compressor by the main engines in flight for the ECS air requirements, in lieu of bleeding the engines. The smaller rating number is indicative of the lower fuel consumption for shaft power extraction compared to bleed-air extraction.

The systems are compared in Figure 115, which shows the ΔTOGW attributable to each as a function of technology level. Systems 2.4.0.1 and 1.4.0.1 are clearly lower in ΔTOGW than any of the others. The installed system weights are compared in Figure 116, in which these two systems again show the lowest weights.

Figure 117 shows the effect on ΔTOGW when the air compressor in System 2.4.1.0 is driven by the main engines in flight compared to bleeding the engines. The TOGW saving (the difference between the two curves) decreases with advancing technology level, and in fact, the two lines eventually cross. This is due to the decrease of the ECS flow requirement from 23 lb/min for Technology Level I to approximately 10 lb/min for Technology Level III. Assurance that the two lines actually cross could not be determined from the limited engine performance data available.

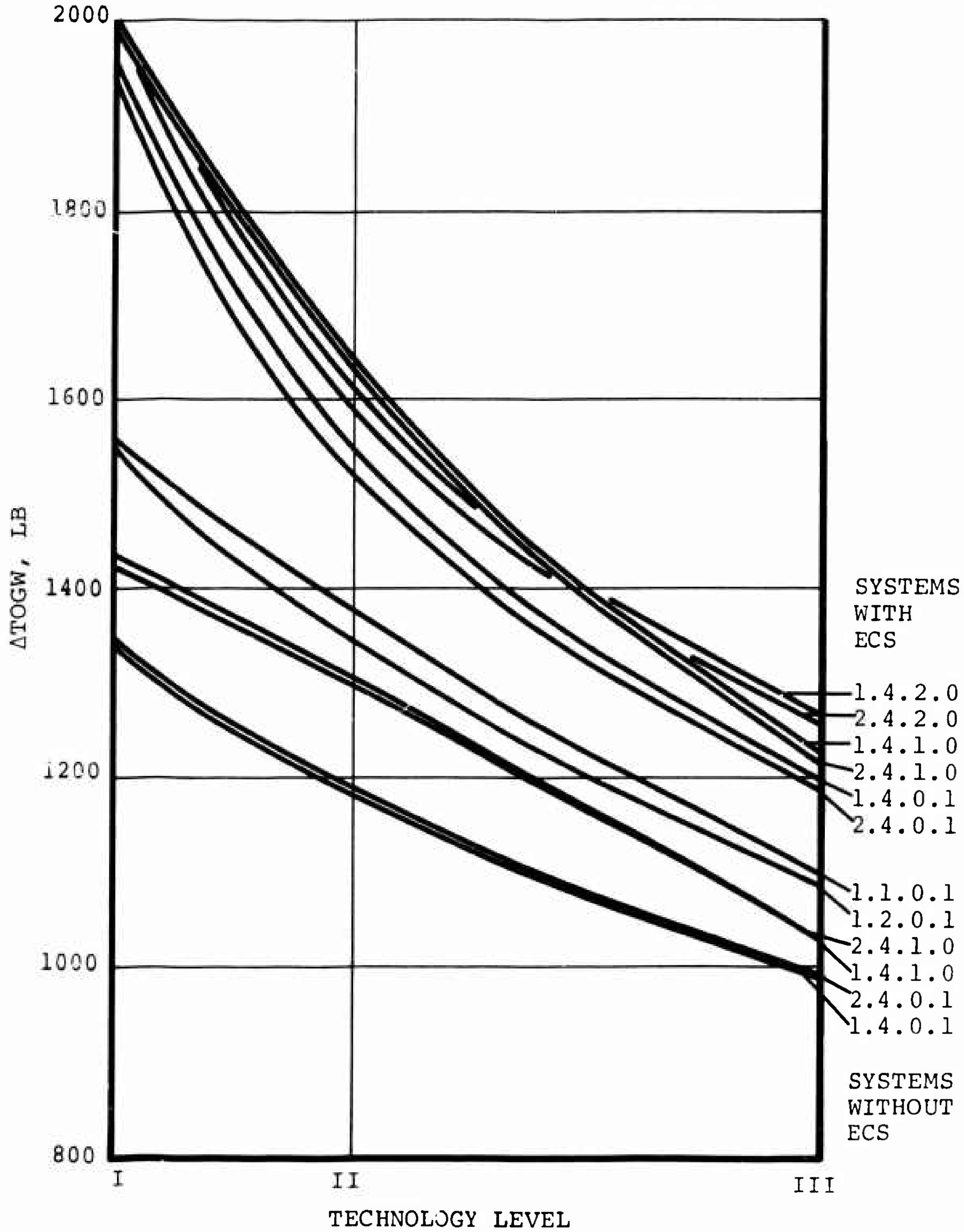

Figure 115. ΔTOGW Comparison, Final Candidate Systems.

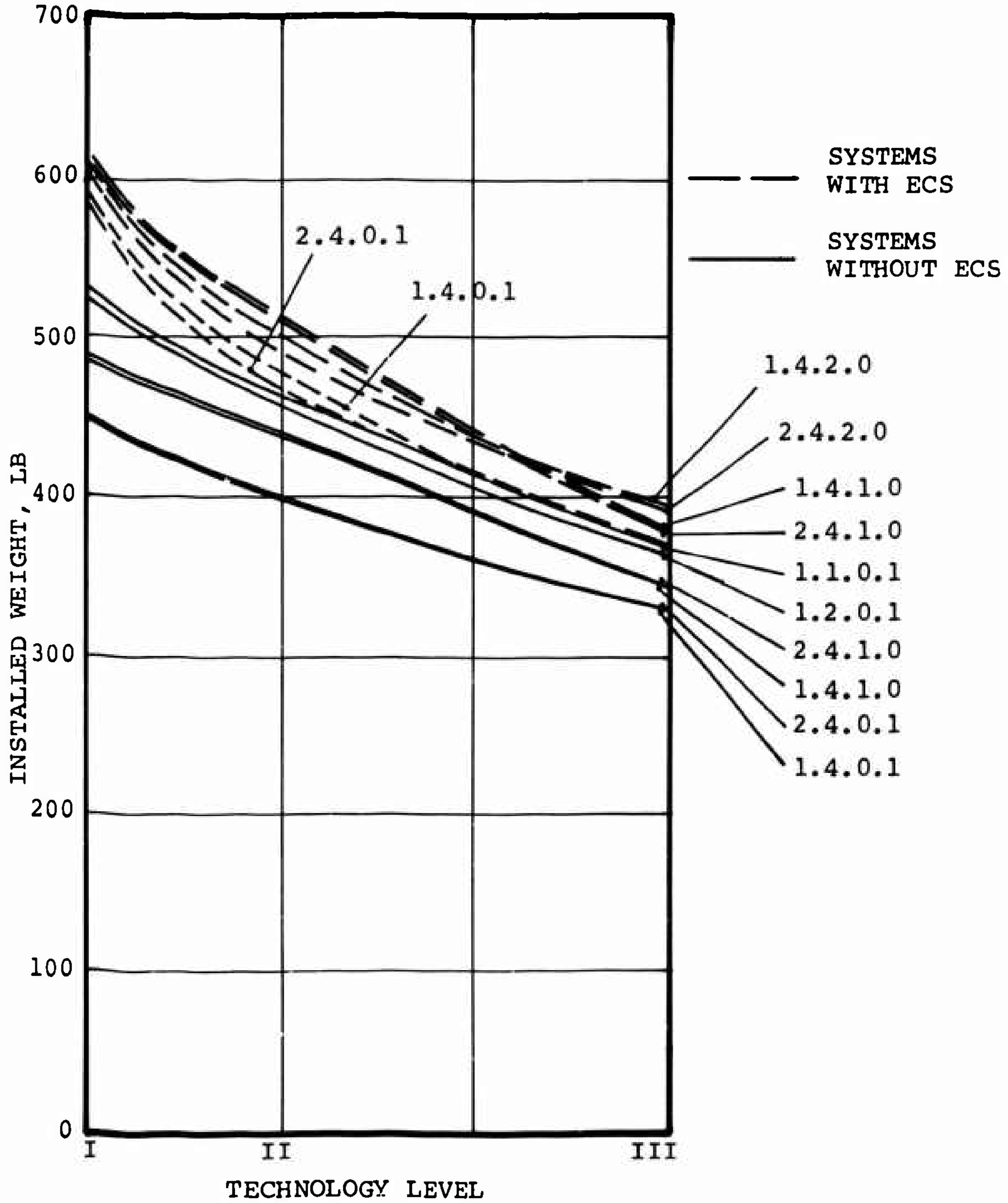

Figure 116. Installed System Weight, Final Candidate Systems.

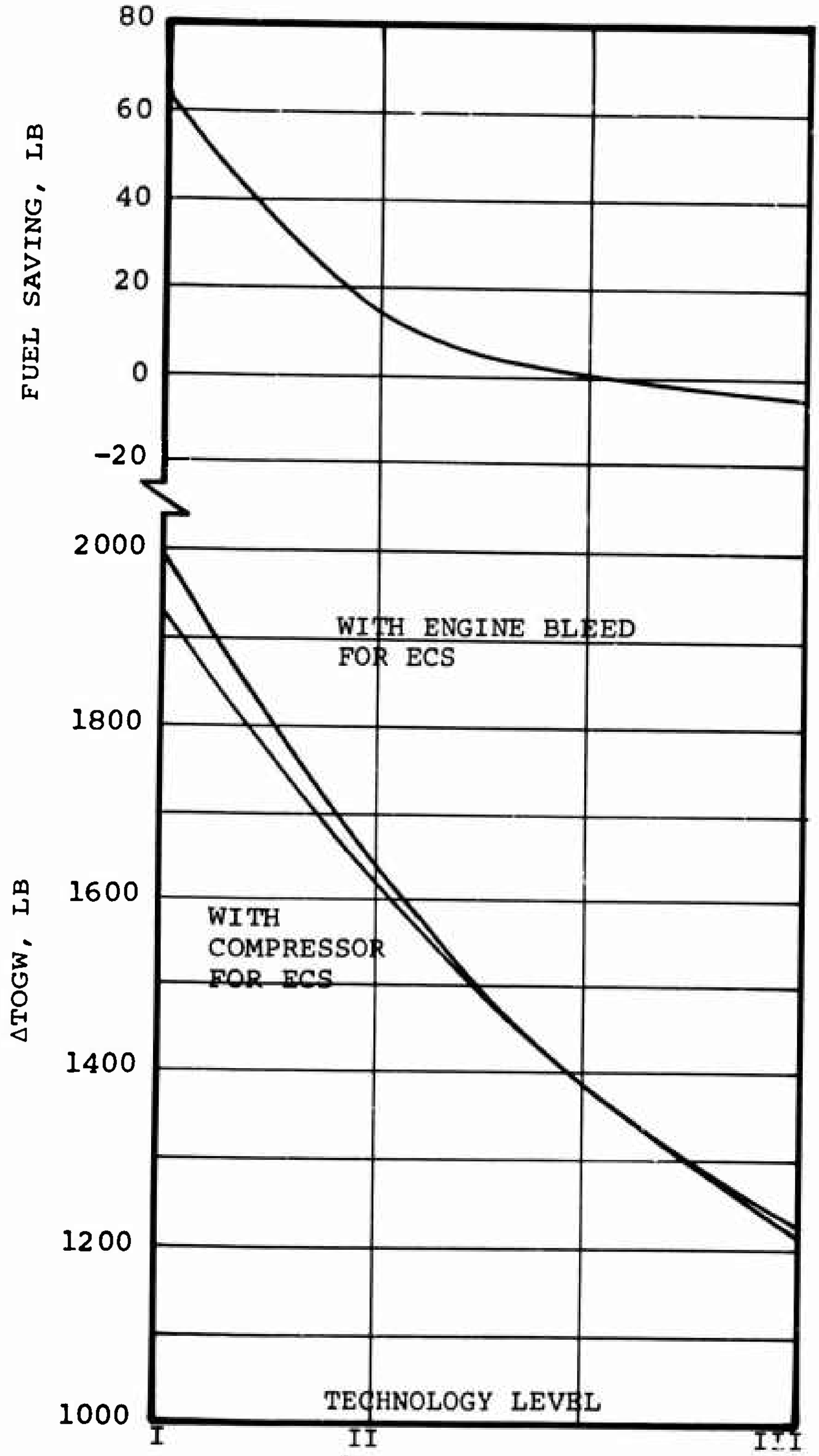

Figure 117. Effect on ΔTOGW and Fuel Used for Furnishing Compressed Air for Recommended System With ECS.

Effect of Adding ECS

The effect of adding ECS is shown on Table LIII by comparing ΔTOGW, the installed weight and volume for the recommended system with and without ECS. Considerable difference in ΔTOGW is shown at the first technology level (602 lb), but this difference decreases with advancing technology to 200 lb. The expendable weight penalty (fuel) accounts for about 40 to 50 percent of the TOGW difference. Furthermore, systems with ECS (Figure 115), begin to exhibit the same ΔTOGW penalty between Technology Levels II and III as that for systems of Technology Level I without ECS.

The effect of technology level on the ECS bleed flow requirement is shown in Figure 118 and compared to air turbine starter flow requirements. The decrease in flow with increasing technology levels is attributable to increase bleed pressure, increased component efficiencies, and, in the case of ECS, use of the recirculation system. The difference between the starter and ECS flows becomes smaller with advancing technology. For Technology Level II, for example, the ECS flow is approximately 3 lb/min greater than the ATS flow, and this difference decreases to about 1 lb/min by Technology Level III. Therefore, the SPS bleed-flow penalty attributed to the ECS becomes quite small.

Comparison of Systems with Hydraulic and Pneumatic Engine Starting

Two systems were selected from the final candidates to compare hydraulic and pneumatic main engine starting. The recommended system, 2.4.0.1 (pneumatic starting), is compared to System 2.4.2.0 (hydraulic starting) without ECS (Table LIV) and with ECS (Table LV). System 2.4.2.0 uses a hydraulic pump on the accessory gearbox to supply hydraulic power to the engine starter motors. In comparisons of ΔTOGW, installed weight and installed volume, the pneumatic system consistently indicated a savings. The smaller savings for systems with ECS are due to the similarity in APU, where both systems required a bleed/shaft power type. The greater differences without ECS are attributable to the requirement for a combustion heater in System 2.4.2.0. Systems with APU bleed available (when an ECS is included) can use a much simpler and lighter weight bleed-air heater.

TABLE LIII. ECS PENALTY FOR RECOMMENDED SYSTEM

System	Technology Level I	Technology Level II	Technology Level III
ΔTOGW			
With ECS	1944	1523	1191
Without ECS	1342	1185	991
ΔTOGW Penalty	602	338	200
INSTALLED WEIGHT			
With ECS	588	469	366
Without ECS	453	398	329
Installed Weight Penalty	135	71	37
INSTALLED VOLUME			
With ECS	7.7	5.7	4.5
Without ECS	5.1	4.6	3.9
Installed Volume Penalty	2.6	1.1	0.6

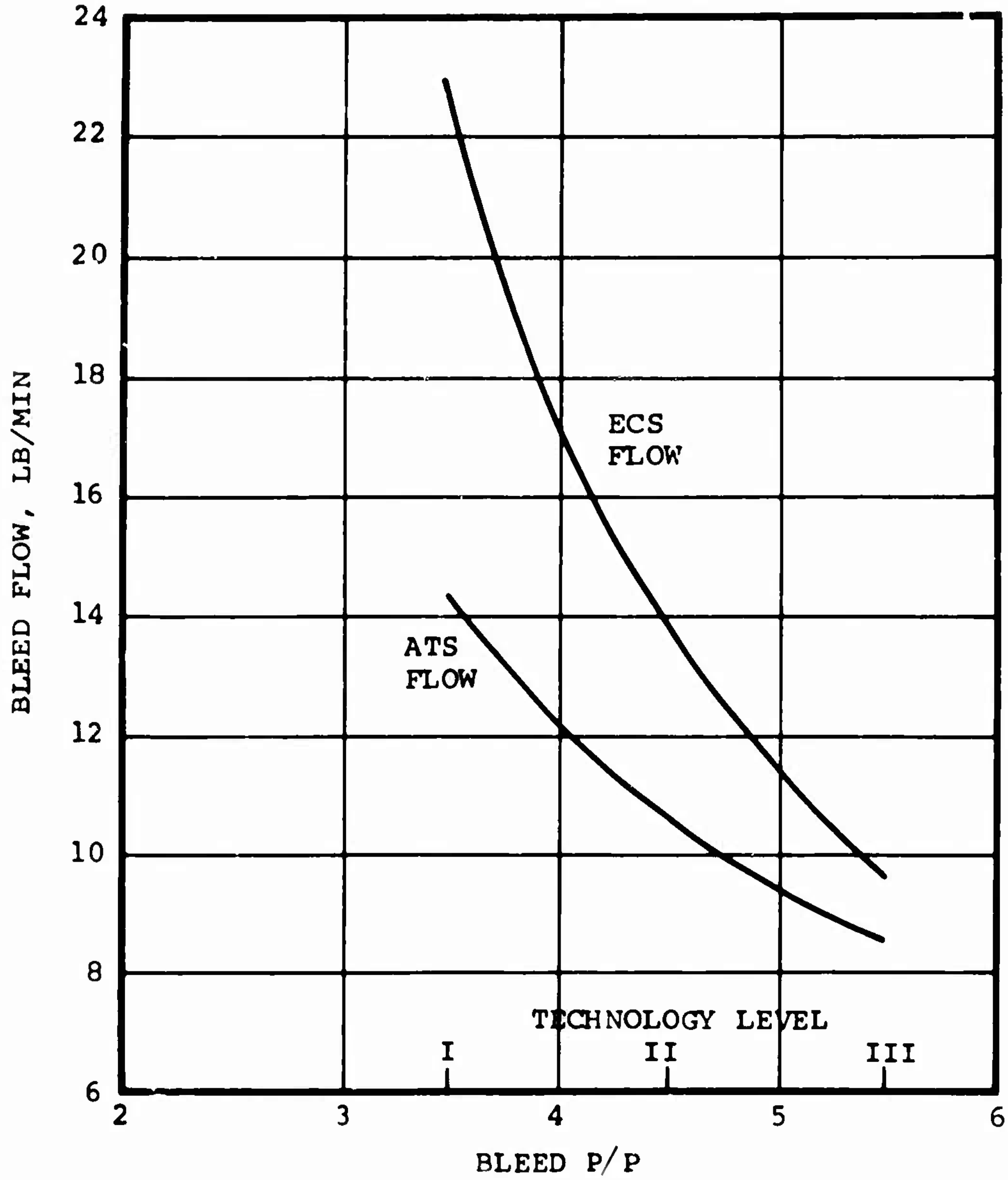

Figure 118. ECS and ATS Flow Requirements for the Recommended System.

TABLE LIV. COMPARISON OF HYDRAULIC AND PNEUMATIC ENGINE STARTING SYSTEMS, WITHOUT ECS

System	Technology Level I	Technology Level II	Technology Level III
SPS TOGW			
Hydraulic Starting (2.4.2.0.)	1541	1423	1171
Pneumatic Starting (2.4.0.1.)	1342	1185	991
TOGW Saving	199	238	180
INSTALLED WEIGHT			
Hydraulic Starting	527	489	397
Pneumatic Starting	453	398	329
Weight Saving	74	91	68
INSTALLED VOLUME			
Hydraulic Starting	6.9	6.6	5.8
Pneumatic Starting	5.1	4.6	3.9
Volume Saving	1.8	2.0	1.9

TABLE LV. COMPARISON OF HYDRAULIC AND PNEUMATIC ENGINE STARTING SYSTEMS, WITH ECS

System	Technology Level I	II	III
SPS TOGW			
Hydraulic Starting (2.4.2.0.)	2005	1588	1259
Pneumatic Starting (2.4.0.1.)	1944	1523	1191
TOGW Saving	61	65	68
INSTALLED WEIGHT			
Hydraulic Starting	611	493	392
Pneumatic Starting	587	469	366
Weight Saving	24	24	26
INSTALLED VOLUME			
Hydraulic Starting	7.9	5.9	4.7
Pneumatic Starting	7.7	5.7	4.5
Volume Saving	0.2	0.2	0.2

8.4 ANALYSIS OF THE RECOMMENDED APU

The APU for the recommended system is a single-spool bleed/shaft configuration. The APU trade-off, emergency power generation in flight, and the coupled APU/ECS concept have been investigated for the recommended APU and system.

8.4.1 Selected APU

The APU for the selected system, 2.4.0.1, is a combination integral-bleed and shaft-power type. The APU and its gearbox will be directly mounted on the accessory drive gearbox. Bleed-air from the APU will be used for main engine starting and for the ECS during the systems checkout mode of operation. It will also supply shaft power to drive the accessories during systems checkout and main engine starting (4-kva electrical power required). The APU gearbox requires a fluid coupling to disconnect the APU from the accessory gearbox during APU starting and main engine operation. The APU will have a hydraulic starting system, as described in Section 6.7.4.

The cycle and configuration of the APU were established in Section 6.7.1. Table LVI summarizes the APU characteristics for the selected system. Figures 82, 83, and 84 are cross sections of the selected APU's for each of the three technology time periods. The major features of each APU configuration are discussed in Section 6.7.1. Figure 119 is a cross section of the gearbox for the recommended APU, showing the fluid coupling, accessory pads, and accessory gearbox mounting pad.

8.4.2 Ground Only Versus Ground and In-flight Use

The two reasons for considering the APU for aircraft in flight are emergency and the secondary power available to provide more main engine power for propulsion and lift.

Various types of in-flight APU power have been considered. The APU can supply the ECS bleed flow and/or the accessory horsepower, or with the power-transmission configuration, the APU could be designed to supply additional shaft power to the main rotor and/or tail rotor while the aircraft is in flight.

Nonregenerated APU

When the main engines are used to supply bleed air for an ECS, a significant horsepower penalty results. On a 95°F day, a bleed extraction of 1.0 percent causes a 3.3 percent decrease in output power. If the APU supplies the bleed-air, the full shaft power of the main engine is available, but a greater

TABLE LVI. CHARACTERISTICS OF SELECTED SYSTEM APU

APU Characteristics	Technology Level					
	With ECS			Without ECS		
	I	II	III	I	II	III
Shaft Horsepower (shp)	32.0	29.5	29.1	16.5	15.9	14.0
Bleed Flow (lb/min)	23.0	14.3	9.8	14.5	10.8	8.8
Compressor Corrected Flow (lb/sec)	1.60	1.00	0.6	0.97	0.70	0.51
Cycle P/P	3.78	4.85	6.01	3.78	4.85	6.01
Bleed P/P	3.52	4.50	5.60	3.52	4.50	5.60
TIT (°F)	1,800	1,890	2,040	1,760	1,860	1,970
Speed (rpm)	62,700	89,500	120,000	80,500	107,000	135,000
Weight (lb)	92.9	55.6	45.7	51.0	40.2	36.0
Volume (ft^3)	1.61	0.71	0.33	0.84	0.46	0.26

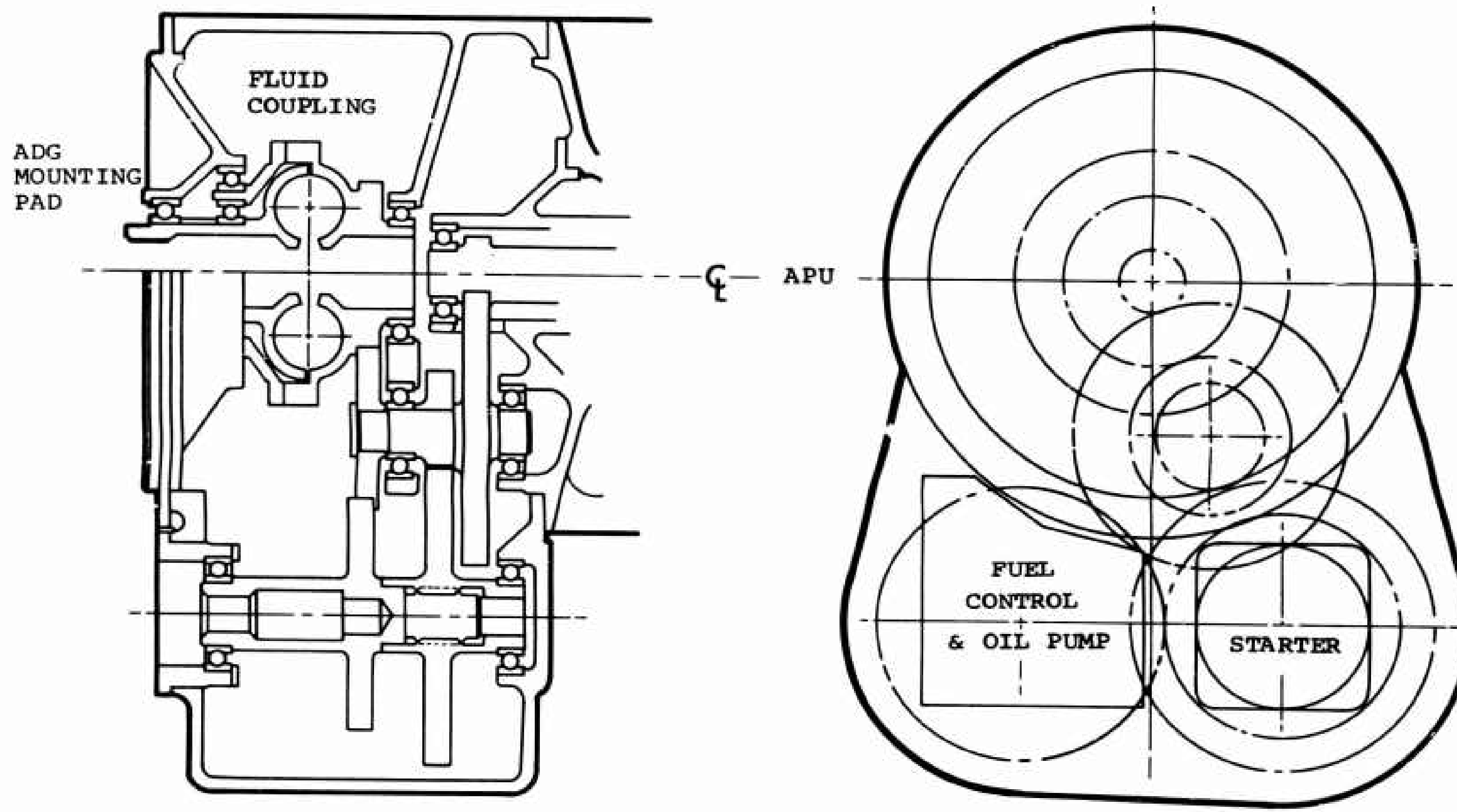

Figure 119. Gearbox for Recommended APU.

amount of fuel is used, resulting in an additional TOGW penalty. This is due to the higher SFC of a small APU relative to the main engine.

Table LVII summarizes the additional TOGW penalty incurred by the APU to supply bleed air while in flight. It is based on the recommended system unchanged with the duty cycle modified to use the APU in flight.

The APU can also supply in-flight shaft power to either the accessories, the main rotor, and/or the tail rotor. There will be an additonal TOGW penalty due to the higher SFC of the APU relative to that of the main engine. In addition to this, a TOGW penalty is associated with the larger APU. Figures 120, 121, and 122 show the characteristics (subject to the restrictions and assumptions at the end of this subsection) of shaft or shaft/bleed APU sized for use in flight. The APU weight and volume curves (Figures 120 and 121) include the APU accessories and gearbox.

For systems without ECS, Figures 123 and 124 give the secondary power system additional weight and volume as a function of APU design horsepower (130°F, sea-level day).

Figure 125 shows the additional TOGW penalty for the recommended system as a function of APU design horsepower, when the APU is used to furnish the accessory shaft power during standby and cruise. If the APU were to be the sole source of aircraft accessory power, it would be sized by the peak accessory loads at the estimated ceiling altitude of 20,000 ft and ambient temperature of -12°F. The maximum accessory shaft power at the APU input pad is approximately 90 shp, consisting of

TABLE LVII. ADDITIONAL TOGW PENALTY, APU FURNISHING ECS BLEED AIR, SYSTEM 2.4.0.1

Technology	TOGW Penalty Ground/In-Flight (lb)	TOGW Penalty Ground Only (lb)	Additional Penalty (lb)
I	2126	1944	182
II	1645	1544	122
III	1279	1191	88

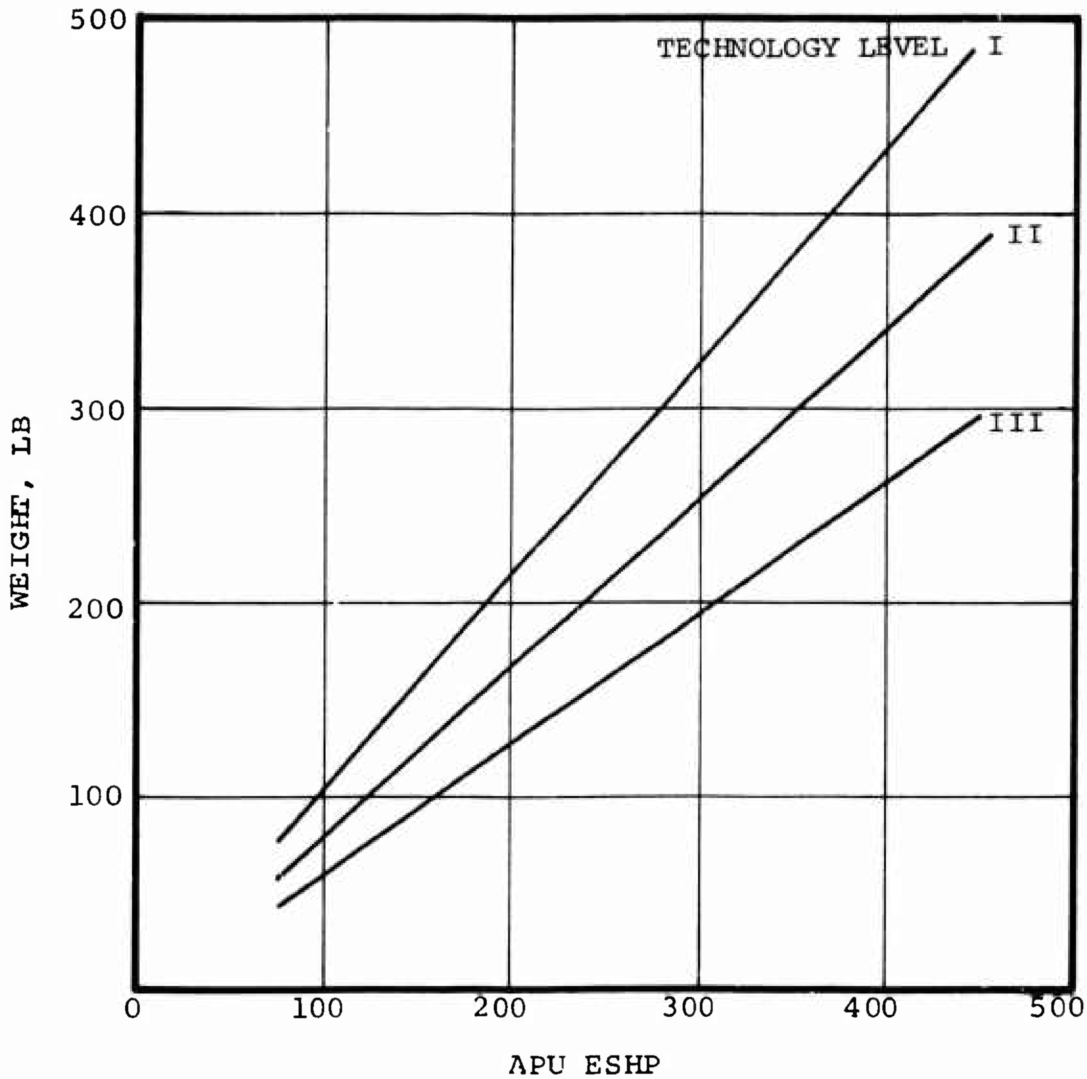

Figure 120. APU Total Weight, In-Flight APU Operation.

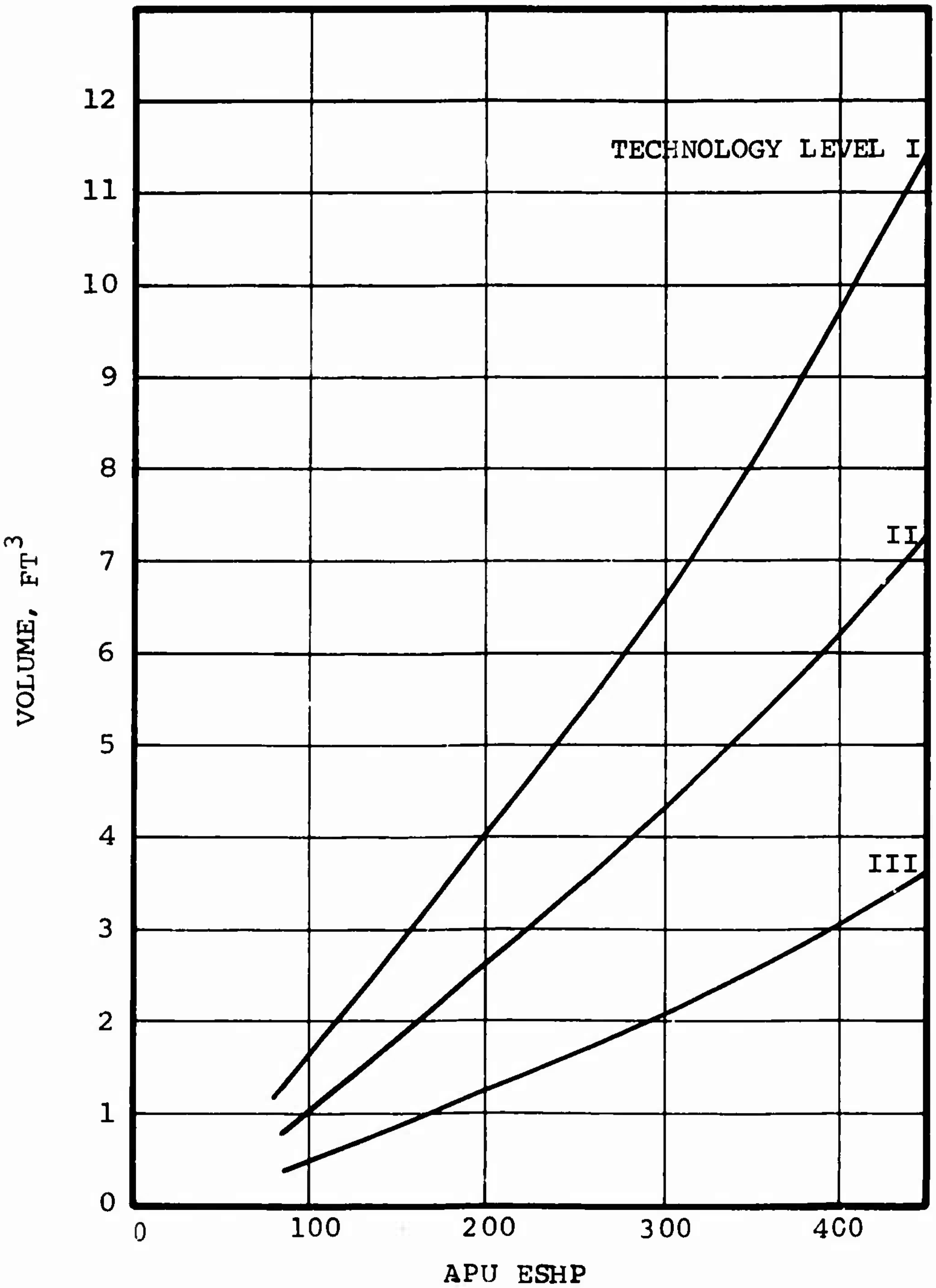

Figure 121. APU Total Volume, In-Flight APU Operation.

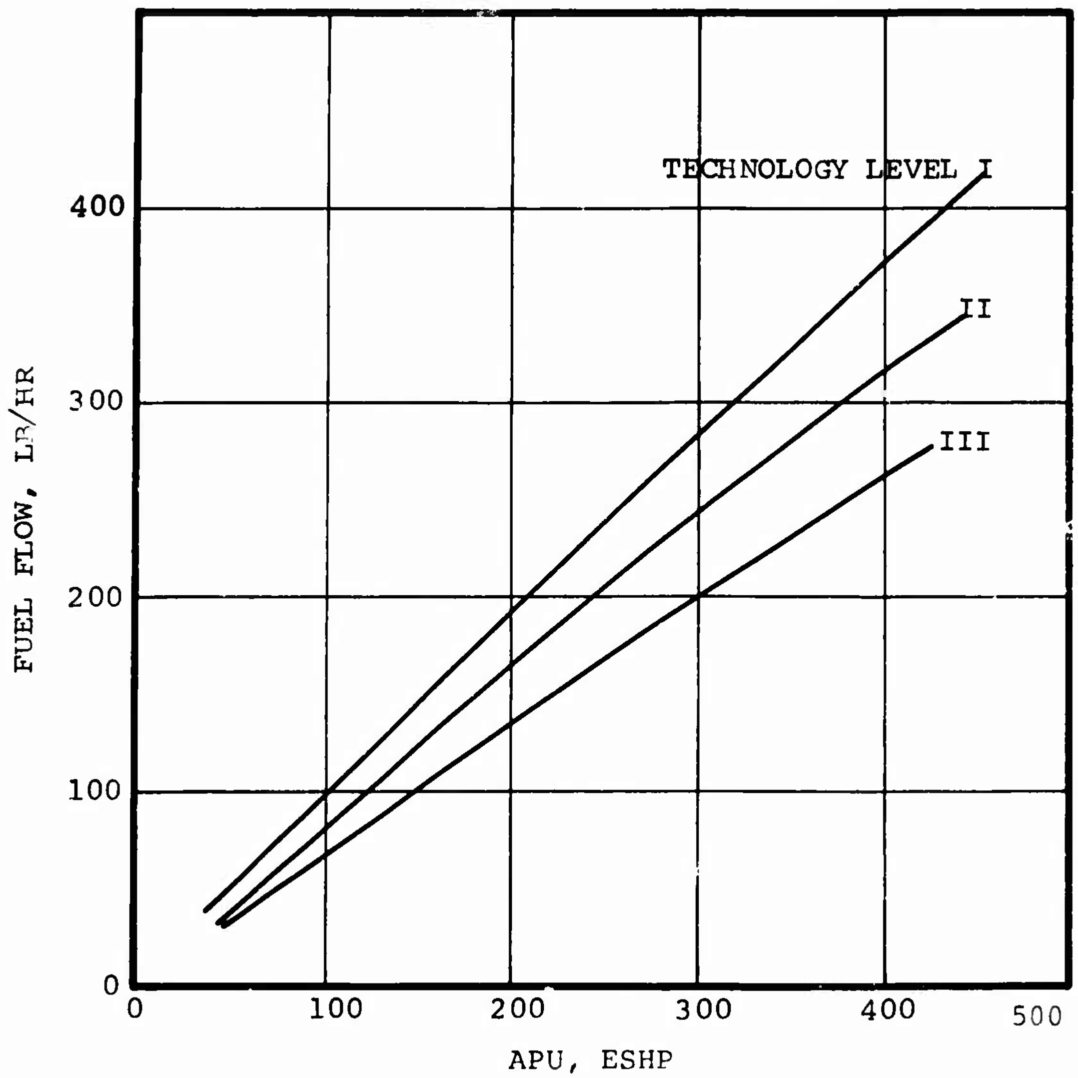

Figure 122. APU Design-Point Fuel Flow,
In-Flight APU Operation.

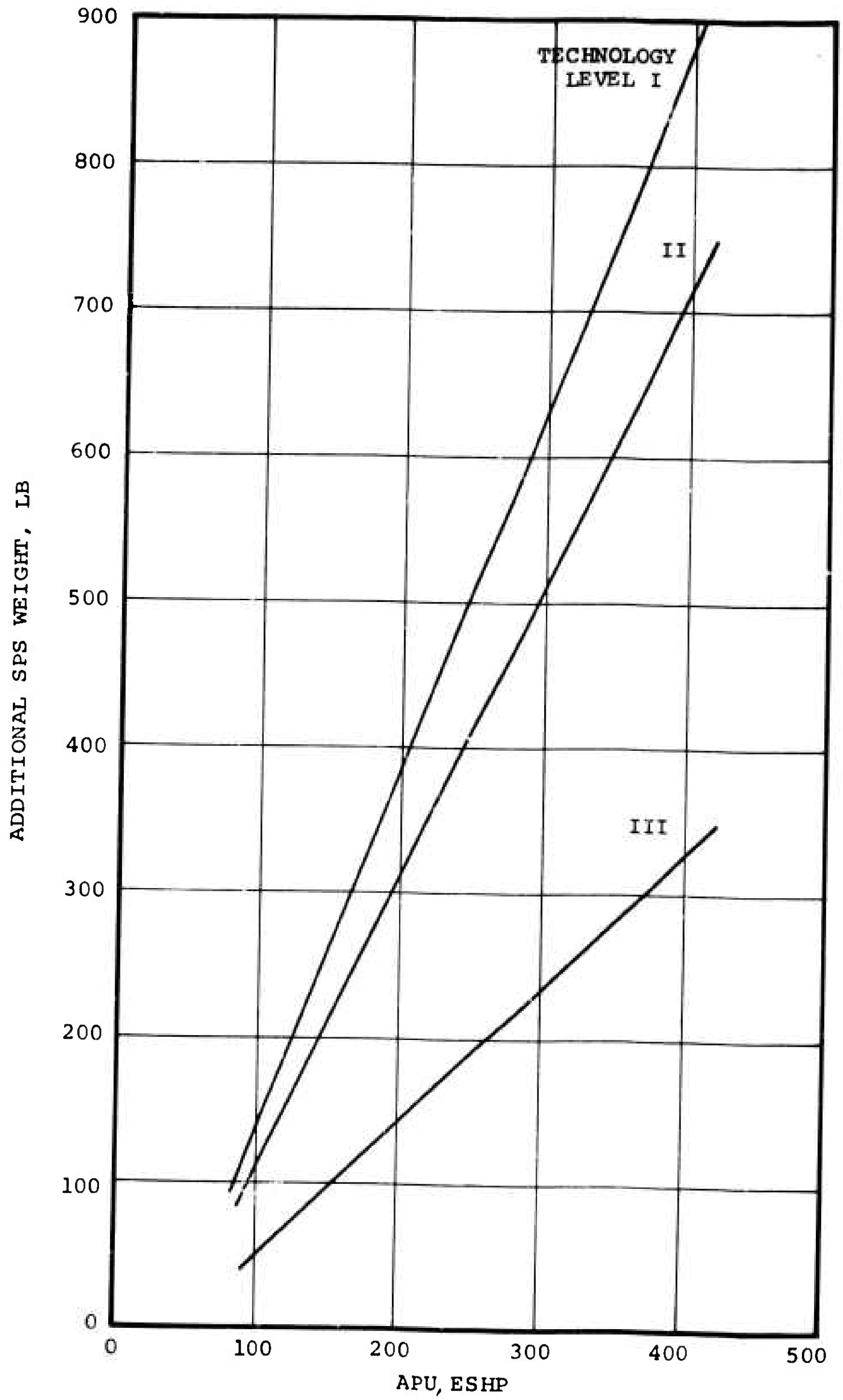

Figure 123. Additional SPS Weight, In-Flight APU Without ECS.

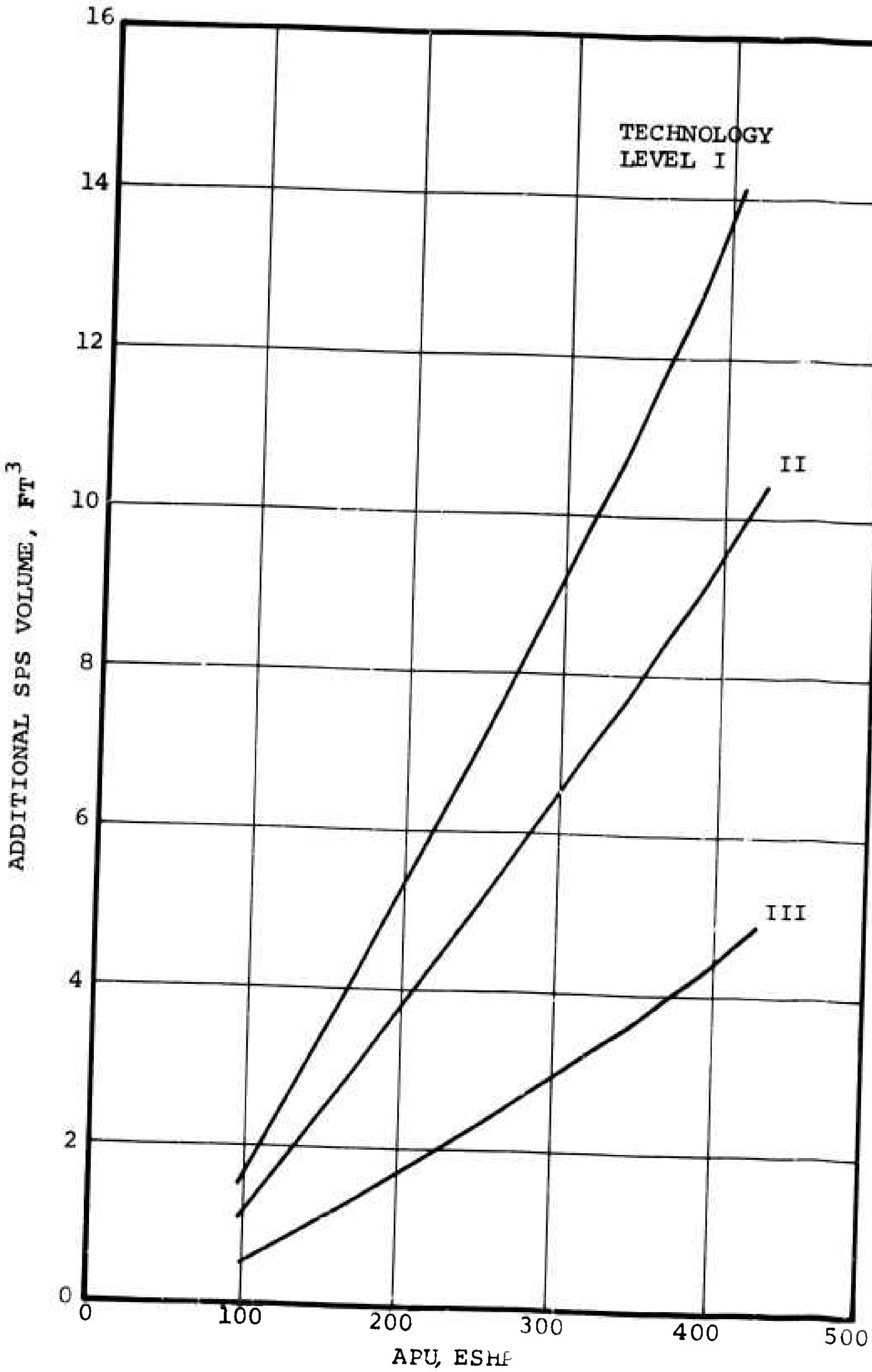

Figure 124. Additional SPS Volume, In-Flight APU Without ECS.

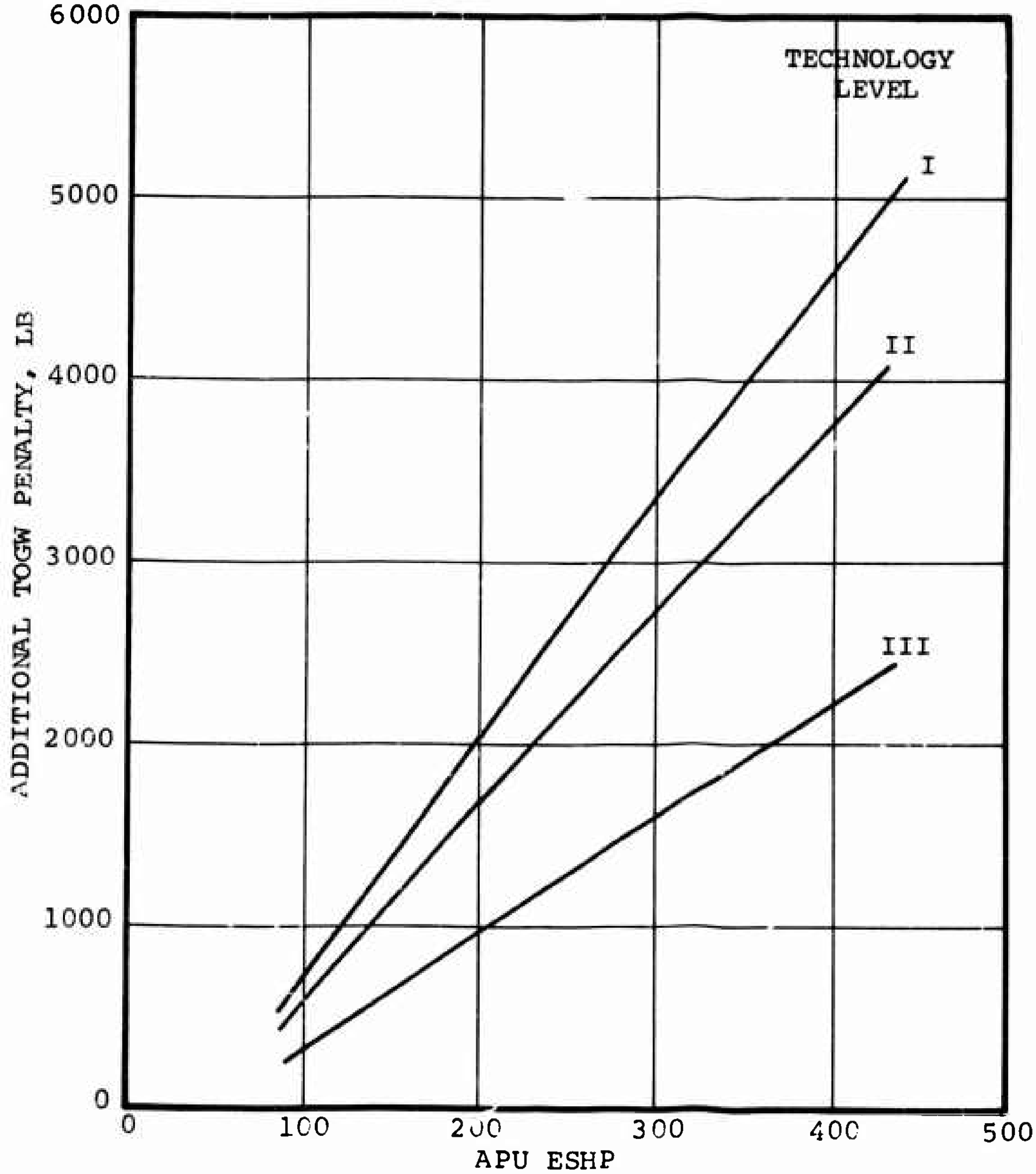

Figure 125. Additional TOGW Penalty, In-Flight APU Furnishing Accessory Power Only, Without ECS.

40-kva electrical load plus 8-gpm hydraulic load plus drag of nonoperating accessories and gearbox losses. Figure 126 is an estimated altitude sizing graph for determining the sea-level APU rating. From this, the 130°F, sea-level APU rating can be obtained for an APU capable of delivering the required accessory horsepower at 20,000 ft and -12°F ambient. From the altitude sizing graph, an APU that supplies 90 shp at the aircraft ceiling must have a 122-shp rating on a 130°F, sea-level day. The additional TOGW penalty, weight, and volume for the recommended system, without ECS (providing the APU furnishes the accessory power) can now be obtained as a function of APU design power (Figures 123 through 125). These figures may also be used if the APU is required to furnish emergency main or tail rotor power in addition to the accessory power in the event of a main engine failure or during a critical aircraft maneuver.

Figure 127 shows the additional TOGW penalty for the system without ECS that uses the APU in flight for main rotor and/or tail rotor power as well as accessory power. For example, an APU sized to drive the tail rotor and the accessories during flight may require a sea-level, 130°F rating of 372 shp--250 for the tail rotor plus 122 for the accessory load at 20,000 ft and -12°F.

For the recommended system with ECS, the APU can be sized to supply either all of the secondary power (accessory shaft power and ECS bleed air) or the secondary power plus main and/or tail rotor power. Figures 128 and 129 give the additional secondary power system weight and volume required when a larger APU, capable of supplying in-flight bleed air and shaft power, is added to the system. The APU characteristics were taken from Figures 120, 121, and 123, using the design-point equivalent shaft horsepower.

For an APU supplying accessory power and ECS bleed air in flight, Figure 130 shows the additional TOGW penalty incurred. The sea-level, 130°F APU rating would be 122 shp (accessory power at 20,000 ft and -12°F) plus the required sea level, 130°F bleed horsepower. Figure 131 gives the additional TOGW penalty for an APU that supplies accessory power, ECS bleed air, and tail or main rotor power. This penalty is based on a continuously running APU operating at maximum power (also applicable to Figure 127). The additional TOGW penalty for an APU supplying accessory power only (Figures 125 and 129) is based on an in-flight APU operating at maximum power only at the aircraft ceiling.

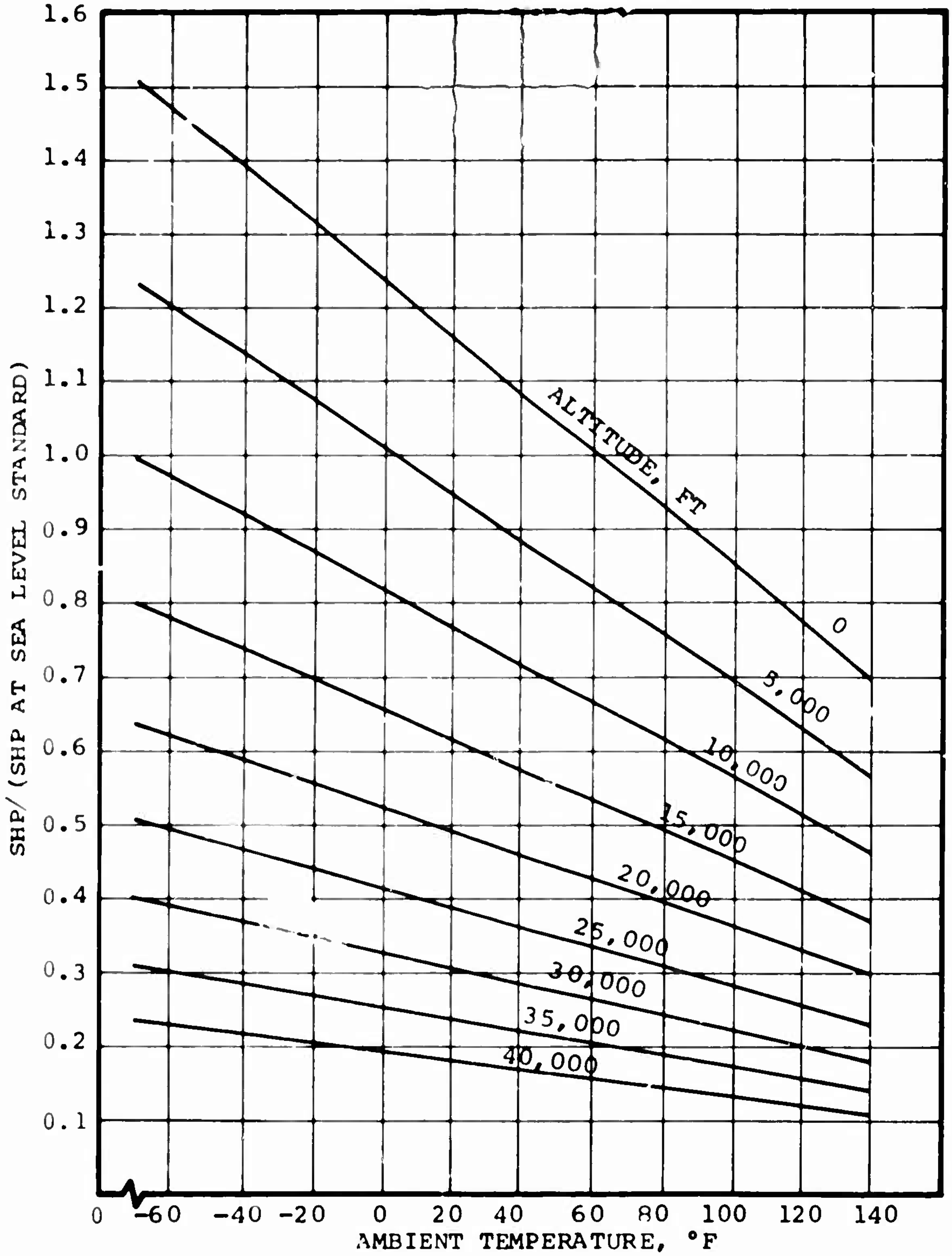

Figure 126. Estimated APU Performance at Conditions Other Than Sea-Level Standard.

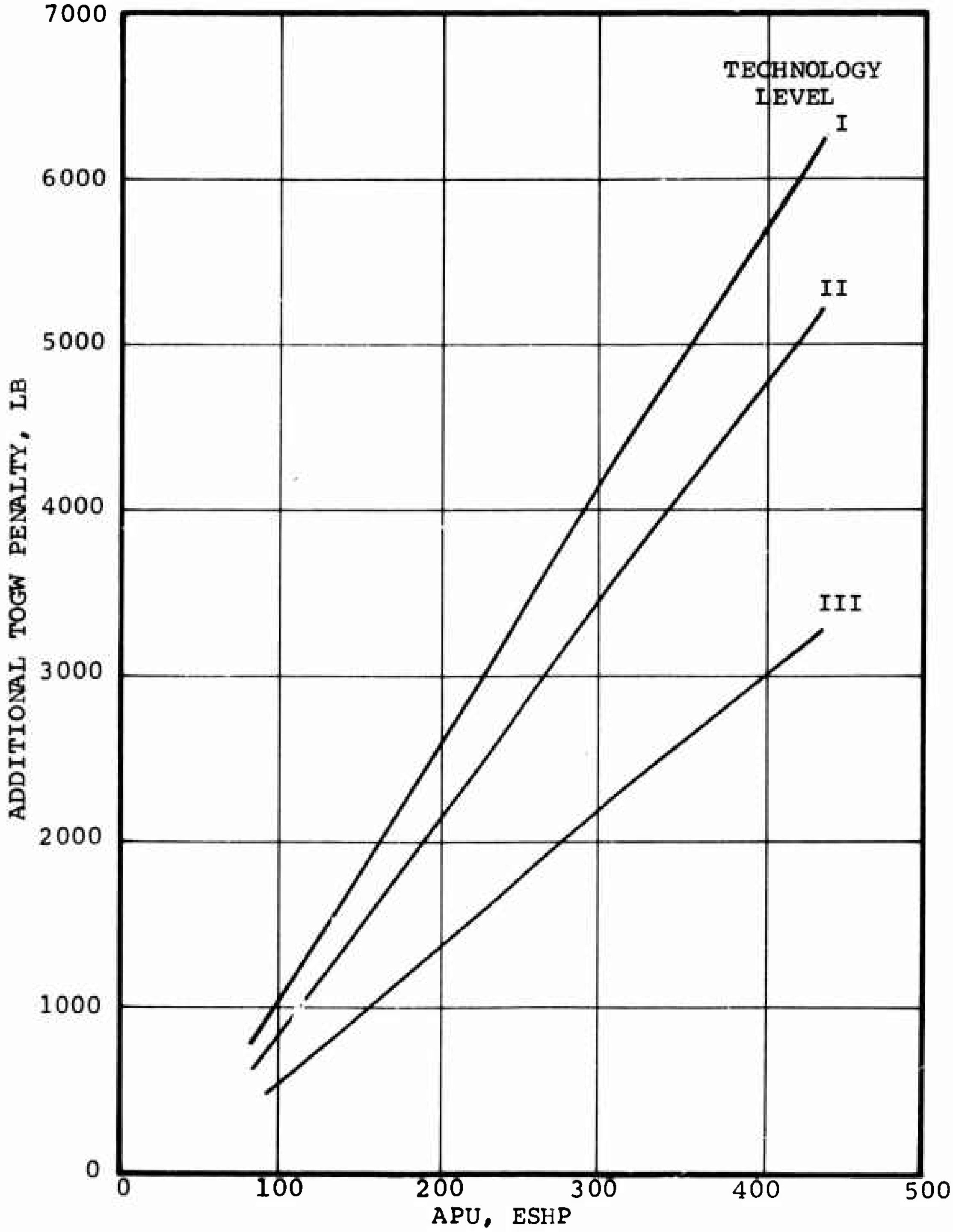

Figure 127. Additional TOGW Penalty, In-Flight APU Furnishing Accessory Power Only, Without ECS.

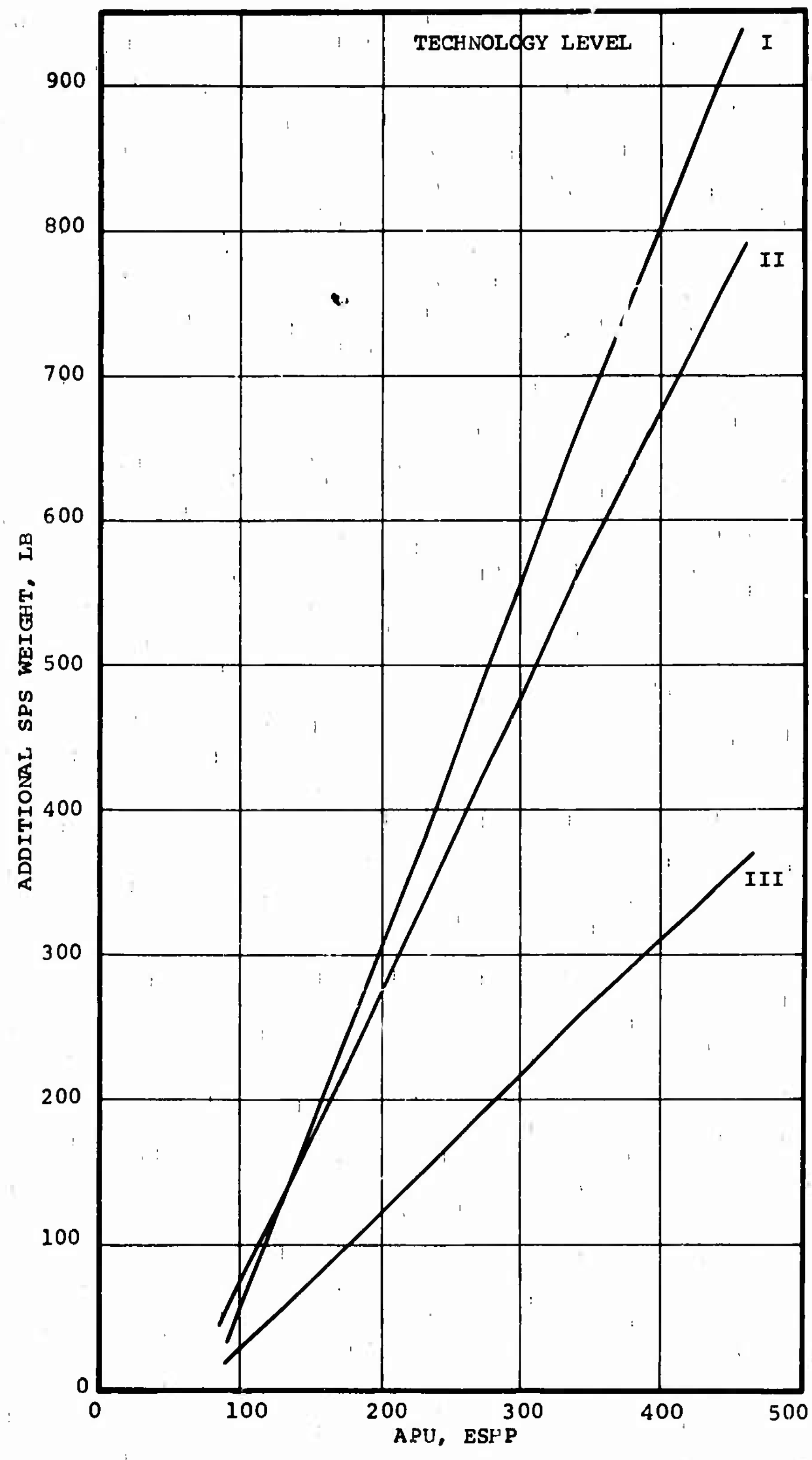

Figure 128. Additional SPS Weight, In-Flight APU With ECS.

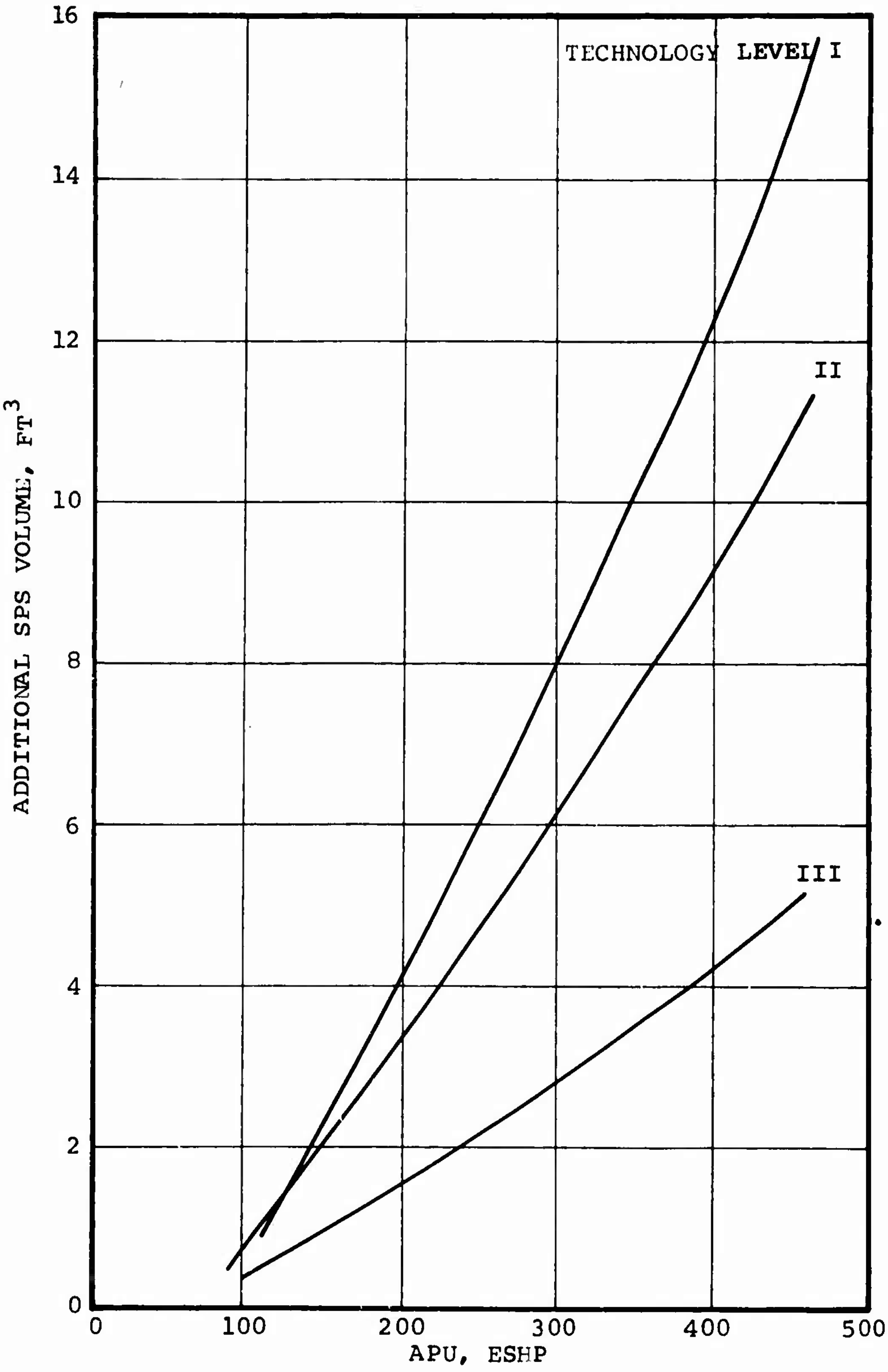

Figure 129. Additional SPS Volume, In-Flight APU With ECS.

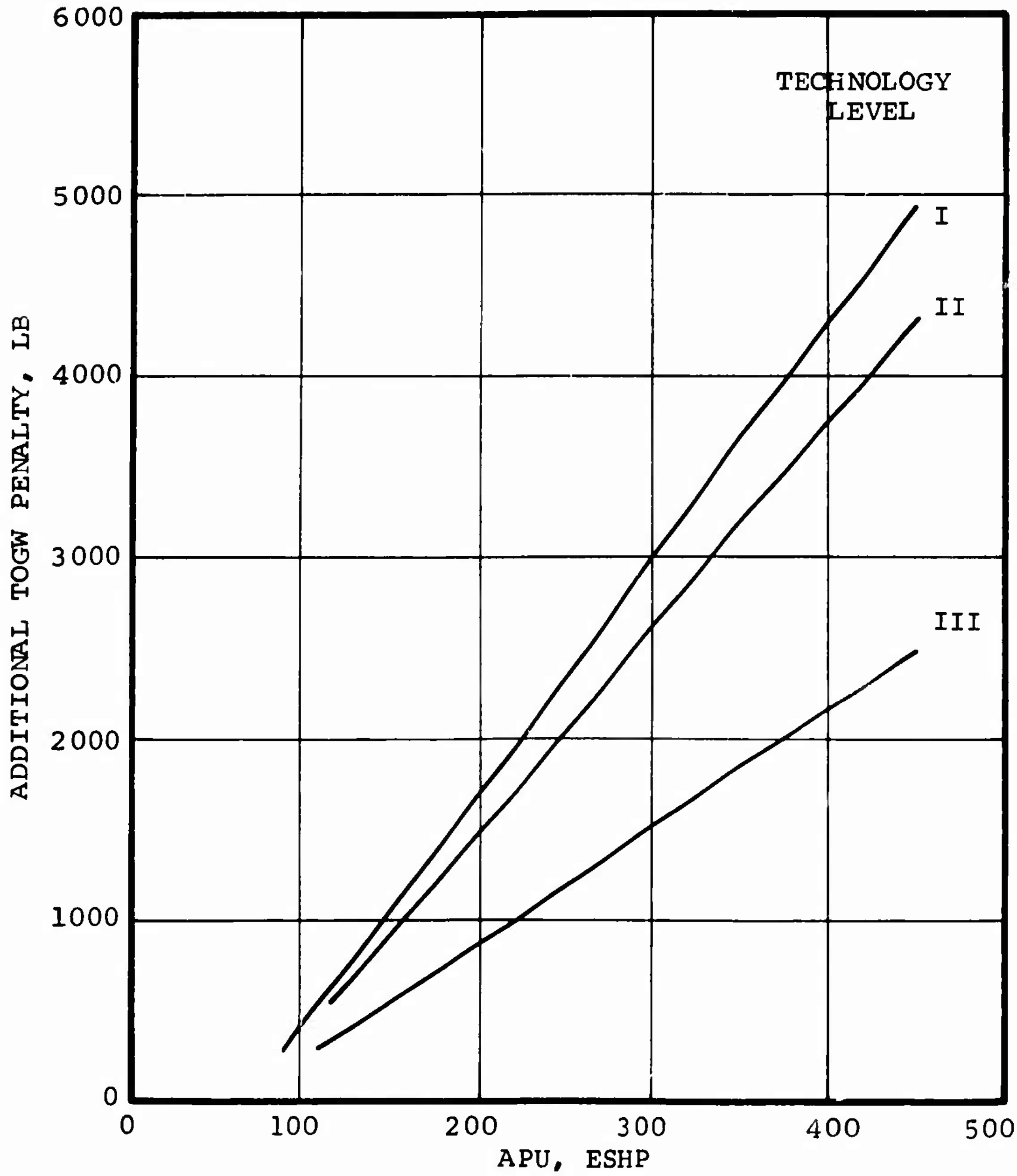

Figure 130. Additional TOGW Penalty, In-Flight APU Furnishing Accessory Power and ECS Bleed Air.

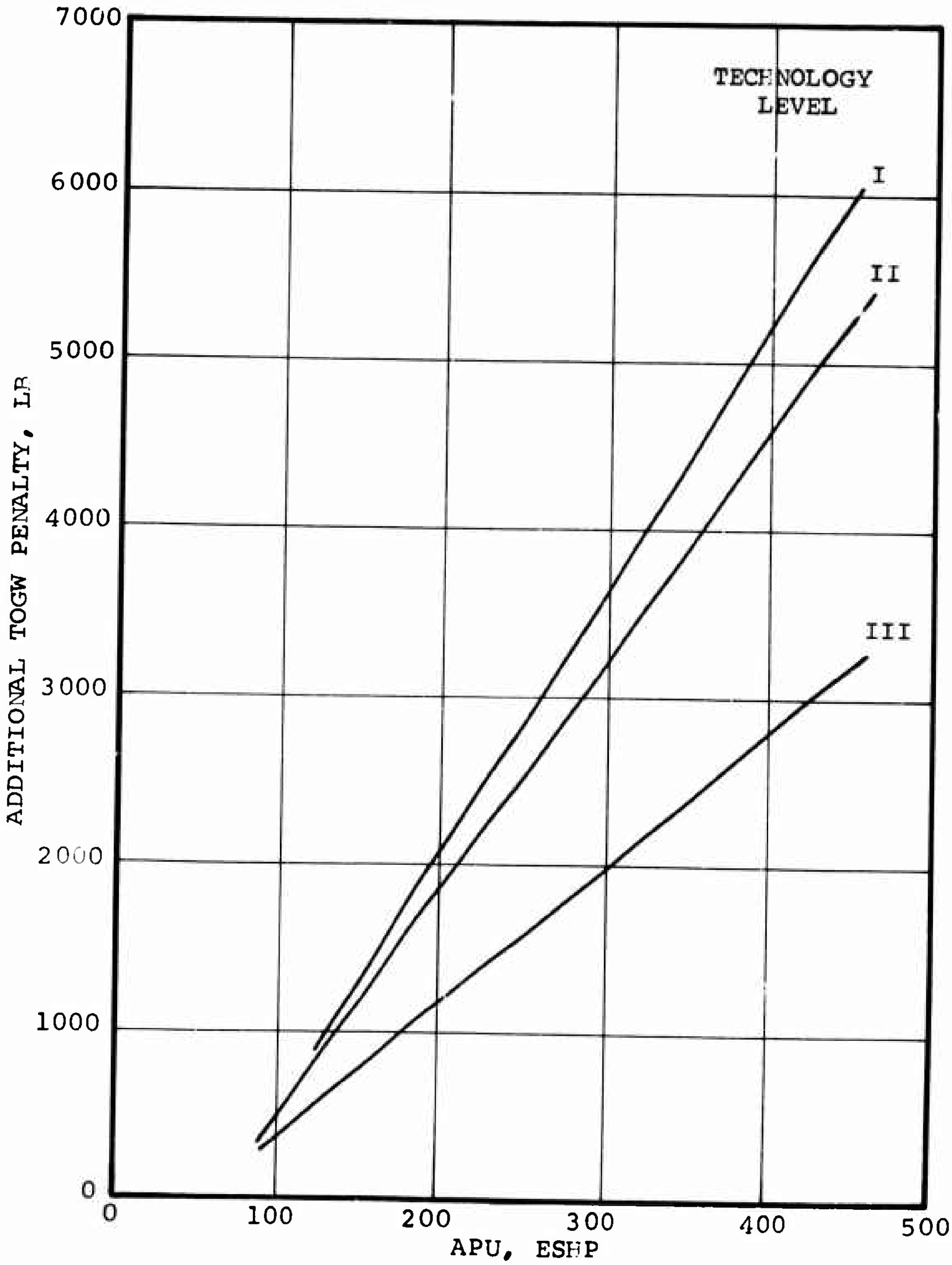

Figure 131. Additional TOGW Penalty, In-Flight APU Furnishing Accessory Power, ECS Bleed Air, and Rotor Power.

Figures 120 through 131 are subject to the following restrictions and assumptions:

1. The configuration and cycle of the APU were established and optimized in Section 6.7.1 for the small size unit required in this application. This configuration and cycle are not necessarily optimum for a large APU supplying additional power during flight.

2. The cycle pressure ratio is limited by the bleed pressure ratio, since the APU must supply bleed air during ground operation for either main engine starting or ECS. The size of an APU supplying in-flight power could be reduced by increasing the cycle pressure ratio to the optimum value for the larger APU. This higher cycle pressure ratio would require a concept such as the notched impeller for extracting bleed flow at the proper pressure ratio.

3. The hydraulic starting system size increases with the APU size increase.

4. The increased APU power rating required more fuel during ground operations, since the APU would be operating at a lower part-load point and would exhibit a correspondingly higher SFC.

5. The additional TOGW penalty does not reflect the possible aircraft TOGW reduction that could be attained by reducing main engine fuel consumption by the amount of power furnished by the APU for the main rotor or tail rotor or by reducing the main engine size by adding a larger APU.

These factors should be considered with Figures 120 through 131.

Regenerated APU

In the regenerated cycle, the APU is larger and heavier than that of the non-regenerated cycle, but the fuel consumption is lower. Figure 132 shows the relation of SFC as a function of heat exchanger effectiveness for the recommended system with ECS. The weights and volumes of the APU are given in Figures 133 and 134. The APU hydraulic starting systems were increased by approximately 30 percent, to account for the larger APU resulting from the decreased specific power of the regenerated cycle. The additional secondary power system weights and volumes are shown in Figures 135 and 136.

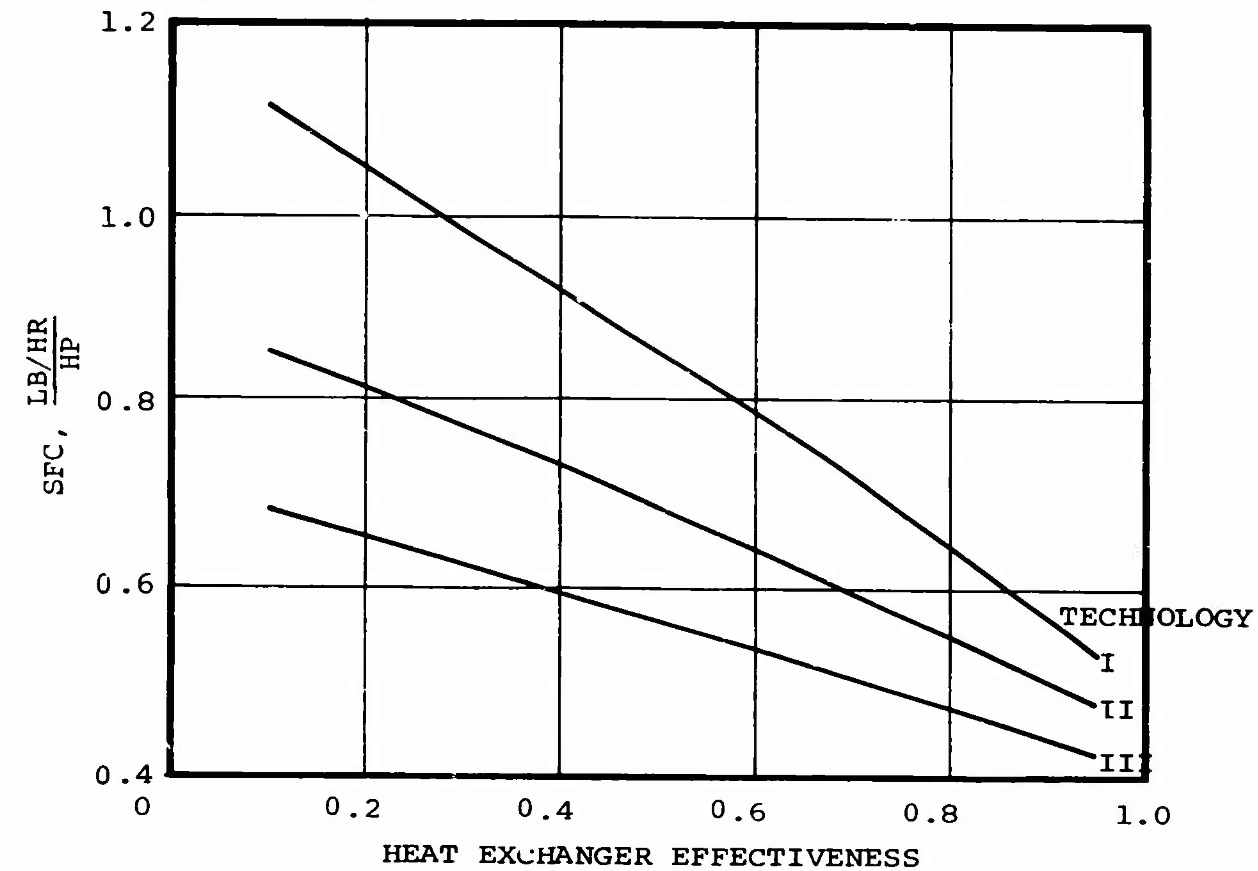

Figure 132. SFC for Regenerated APU.

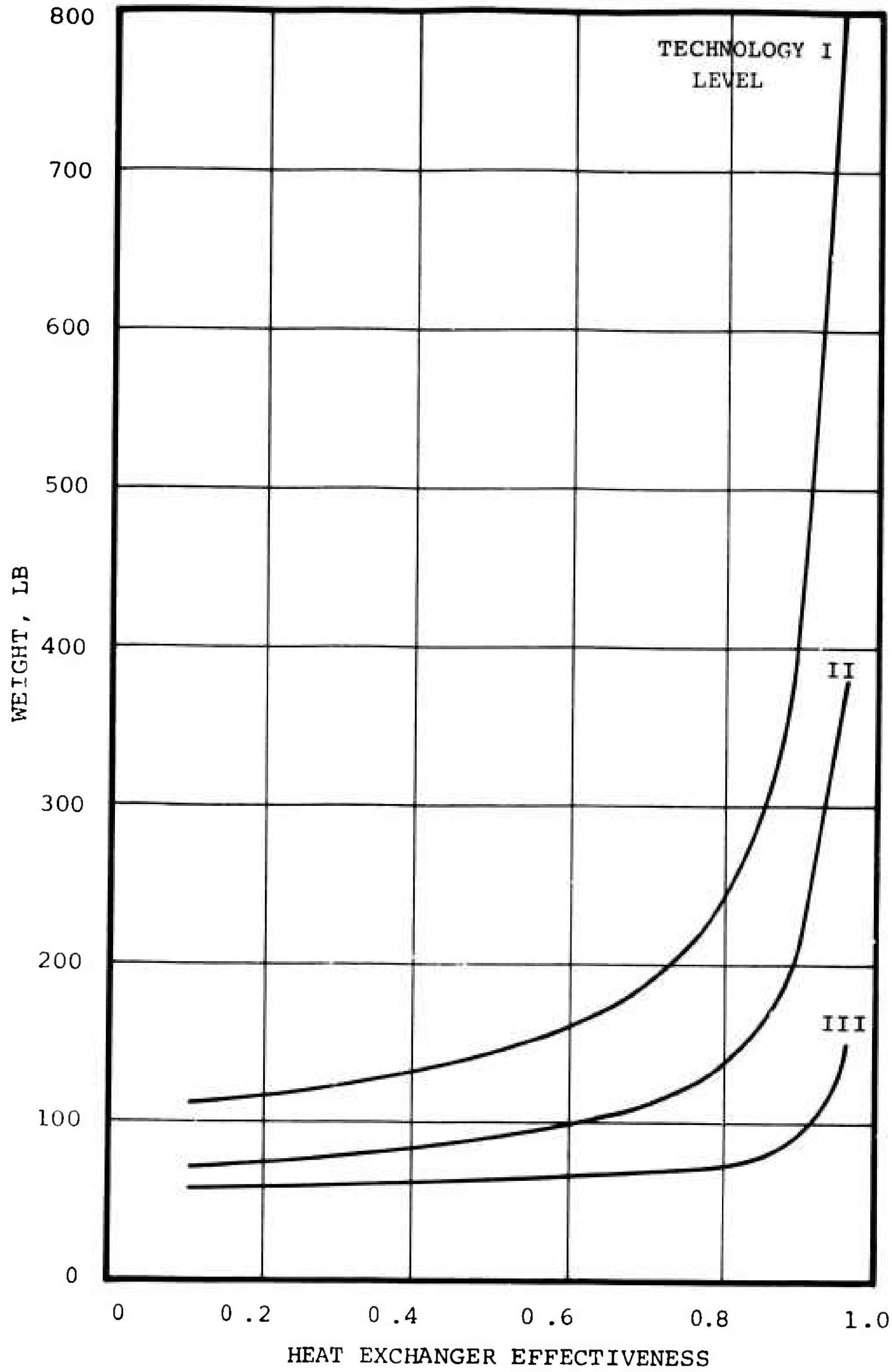

Figure 133. Total APU Weight, Regenerated APU.

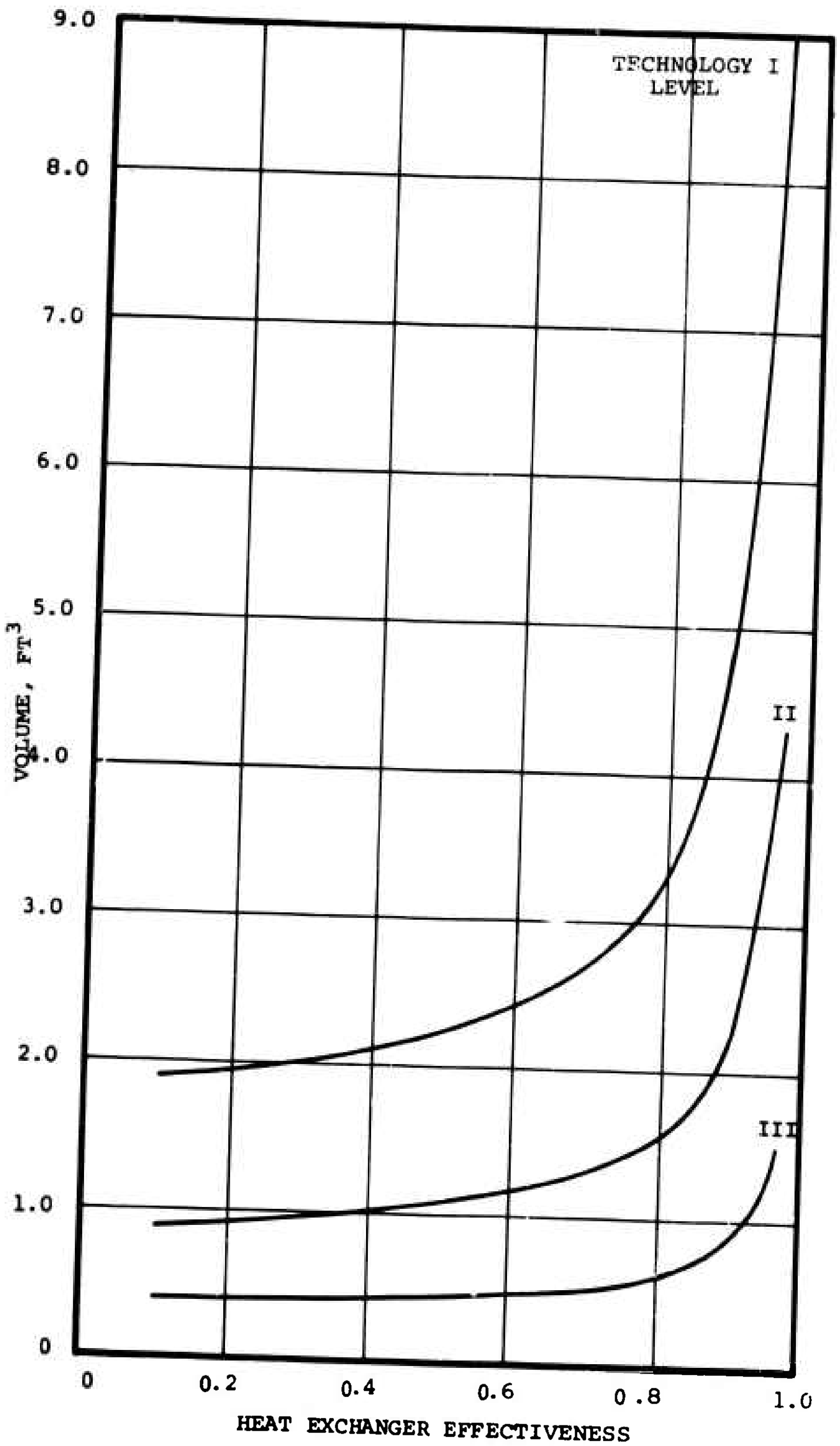

Figure 134. Total Volume, Regenerated APU.

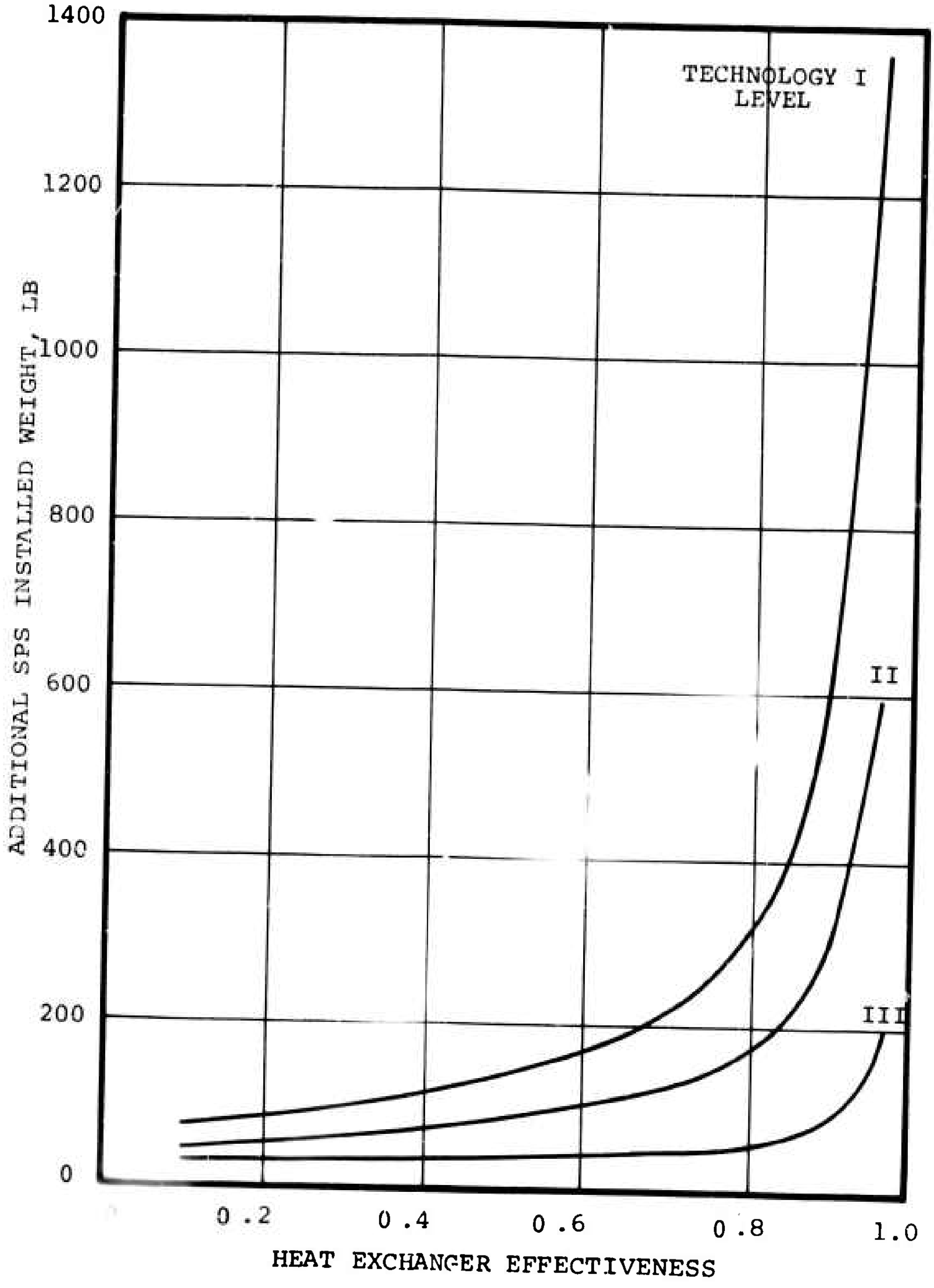

Figure 135. Additional SPS Installed Weight, Regenerated APU Furnishing Ground or In-Flight Power.

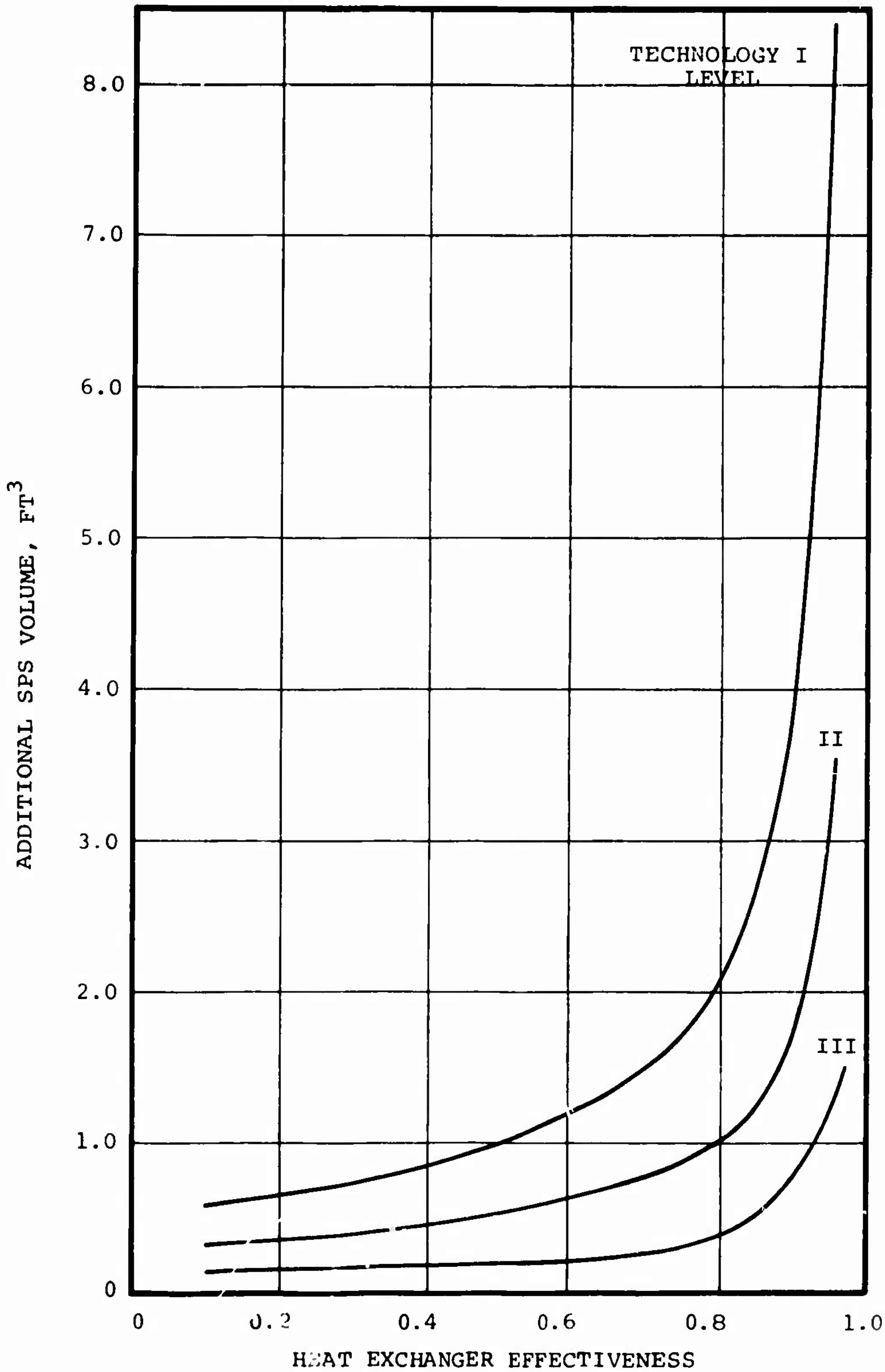

Figure 136. Additional SPS Volume, Regenerated APU Furnishing Ground or In-Flight Power.

The regenerated cycle would be advantageous if the fuel saving, made possible by the lower SFC, would offset the weight penalties resulting from the lower specific power and larger APU. Since the TOGW penalty is a function of both fuel consumption and system installed weight, it will minimize at an optimum heat exchanger effectiveness if the fuel saving offsets the added weight.

Figure 137 is a plot of additional TOGW penalty as a function of heat exchanger effectiveness for the recommended system with ECS when the APU is used for ground power only. The curves illustrate that the TOGW penalty of the regenerated cycle is greater than that of the non-regenerated cycle for all values of heat exchanger effectiveness. Figure 138 is similar except that the APU, while in flight, supplies the ECS bleed-air. Comparing these curves with the additional TOGW penalties listed in Table LVII for the non-regenerated cycle (Standard) reveals that the added TOGW penalty is greater for the regenerated cycle.

The conclusion from this analysis is that, for this application, the added weight of the regenerated cycle is not offset by the reduced fuel flows. The mission of the aircraft is not long enough to allow the regenerated cycle low SFC to offset the added secondary power system weight. Other considerations, such as reliability, maintainability, and vulnerability, would be adversely affected by adding a heat exchanger to the APU. Therefore, the regenerated APU is not recommended for this application.

8.4.3 Emergency APU In-Flight Operation

In the event of the loss of either or both main engines while in flight, the APU, as sized for the normal duty cycle, could provide emergency accessory power. When sized for in-flight power generation, the maximum accessory power loads could be met by the APU, but when sized for ground use only, a small portion of the sea-level accessory power will be available. Since the systems without ECS require the smallest APU, the lowest level of emergency power will be available. If both main engines should fail, autorotation would provide a certain amount of lift and prevent the helicopter from going into free-fall. The effectiveness of the autorotation would be increased by using the APU to provide the emergency accessory power for aircraft control instead of the rotor.

The minimum emergency power requirements for aircraft control have been estimated as follows:

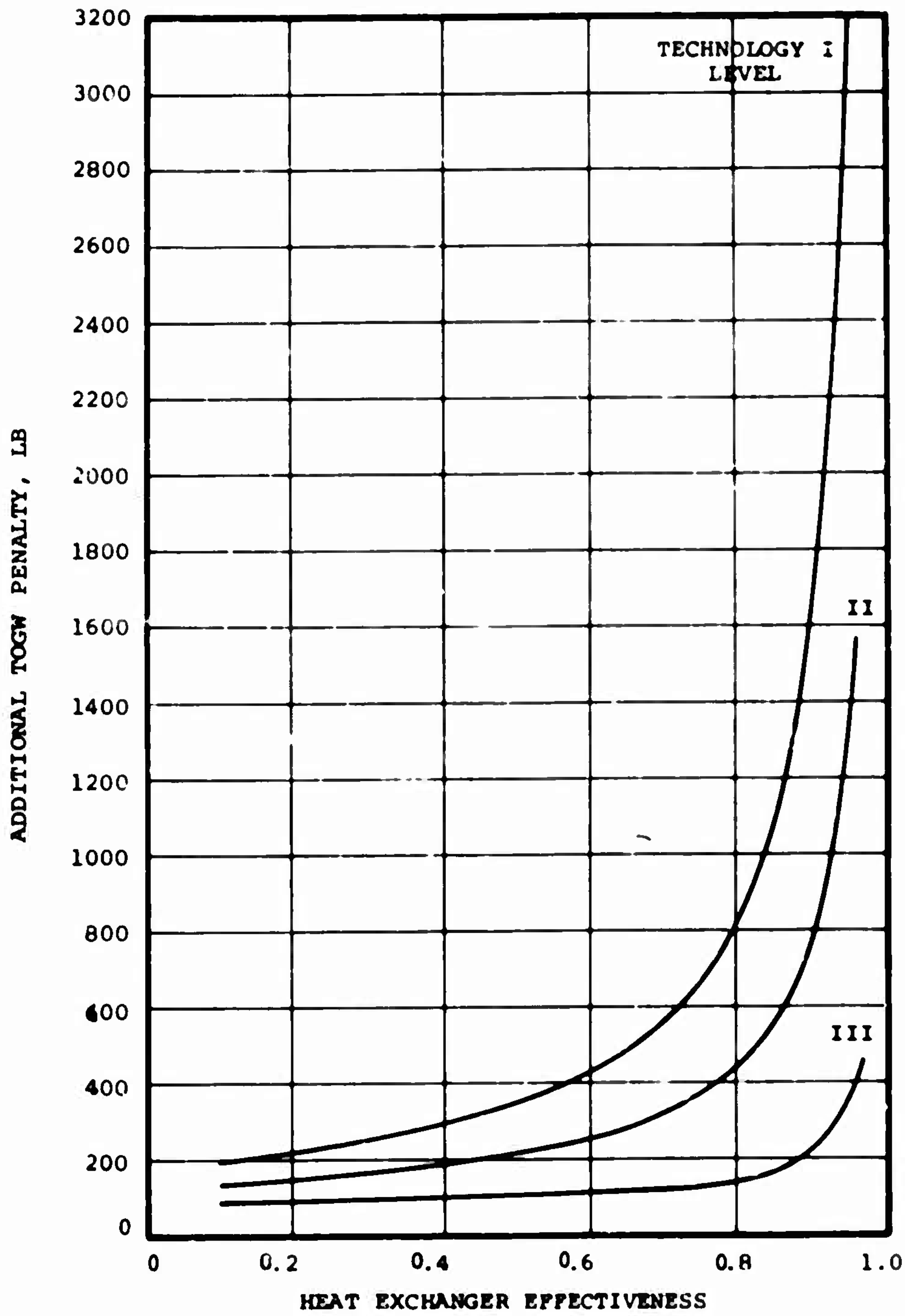

Figure 137. Additional TOGW Penalty, Regenerated A'J Furnishing Ground Power Only.

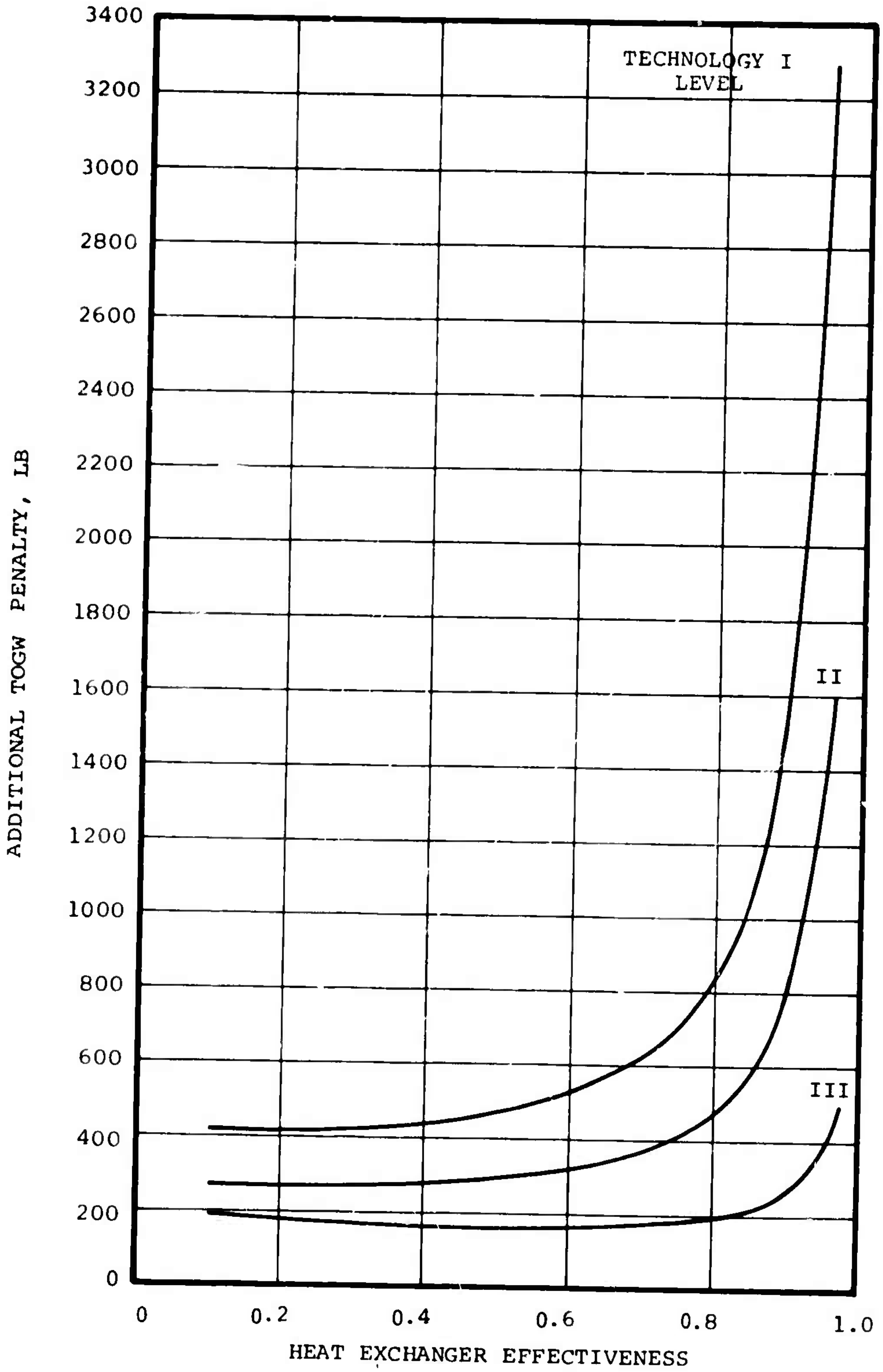

Figure 138. Additional TOGW Penalty Regenerated APU Furnishing Ground and In-Flight Power.

1. Hydraulic - 5 gpm for controls

2. Electric - 3-kva ac power for fuel boost pump, cockpit instrumentation, and controls; the onboard battery will supply dc power during this mode

The power that must be furnished by the APU to supply these emergency requirements ranges from 21 shp for Technology Level I to 19 shp for Technology Level III.

Figure 139 is a curve of the estimated power reduction as a function of altitude for the APU (based on Figure 122). For a bleed/shaft APU of this type, approximately 85 percent of the eshp is available as shaft power, the remaining being dissipated as surge bleed. Utilizing this value in conjunction with design-point eshp listed in Table VIII, the maximum available APU shaft horsepower on a 130°F, sea-level day without ECS for Technology Level I is 38.3. From Figure 139, 67 percent of this (25.8 shp) is available at the aircraft control. For the Technology Level III APU without ECS, 22 shp is available at the aircraft ceiling and only 19 is required for control. For systems with ECS, the APU's are larger and can supply any excess power needed.

It is, therefore, concluded that the APU's for the selected systems can meet the minimum estimated emergency power requirements.

8.4.4 APU/ECS Concept

In the standard ECS, the power from the expansion turbine is absorbed by some type of loading device. For the simple air cycle, the loading device is a fan which supplies air to the heat exchanger in the system. This concept is illustrated in the standard approach shown in Figure 140. In the coupled approach (Figure 141) the expansion turbine shaft power is fed back, either into the APU gearbox or the accessory drive gearbox, and the heat exchanger fan is supplied power from either.

With the standard approach (Figure 140), compromises must be made in the design of both the expansion turbine and the fan. Normally, a fan of this type is of high efficiency, with low rpm design. However, the fan must absorb the expansion turbine shaft horsepower at the expansion turbine speed. This dictates the design criteria for the fan and results in a lower efficiency device. The expansion turbine design is also compromised in that it is designed for a speed lower than that required for maximum efficiency. The net result is a compromise in the design of both components.

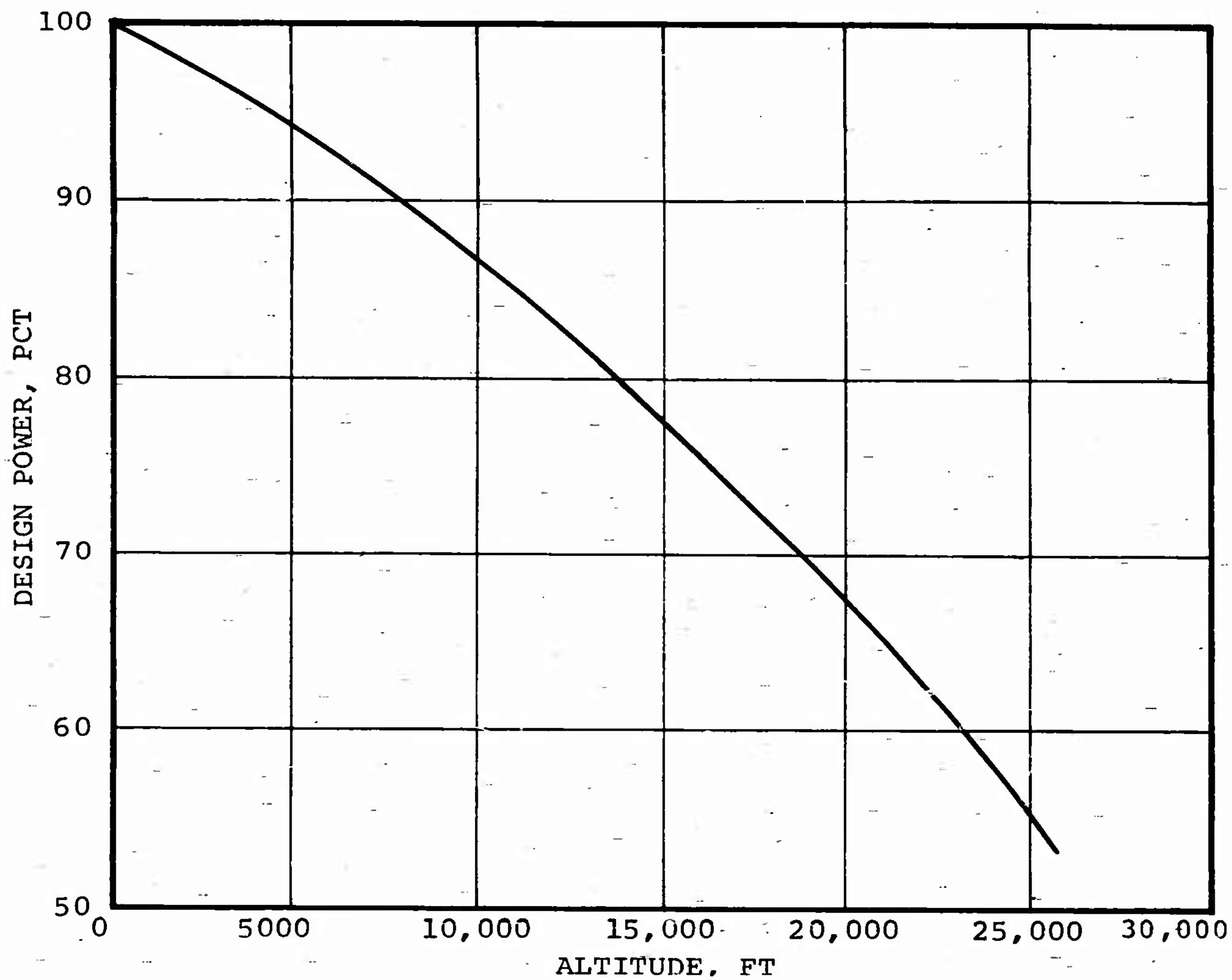

Figure 139. Estimated APU Power Reduction as a Function of Altitude, Hot-Day Conditions.

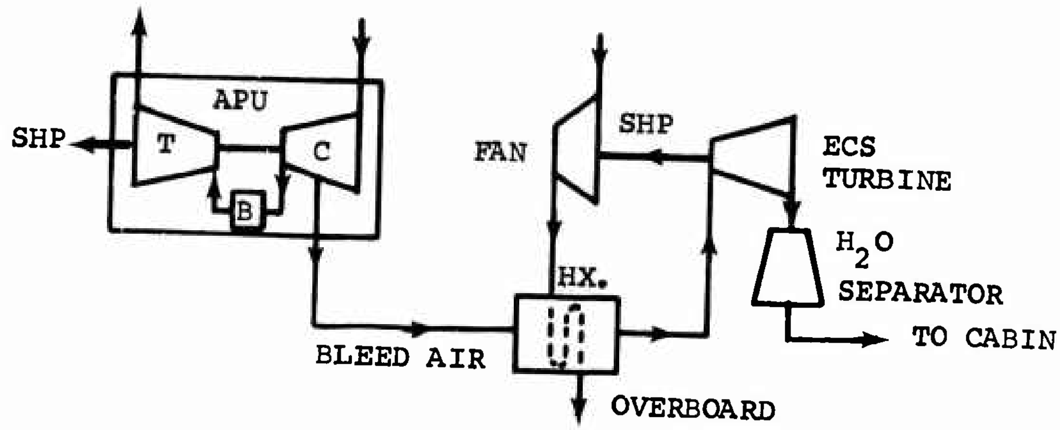

Figure 140. ECS Standard Approach.

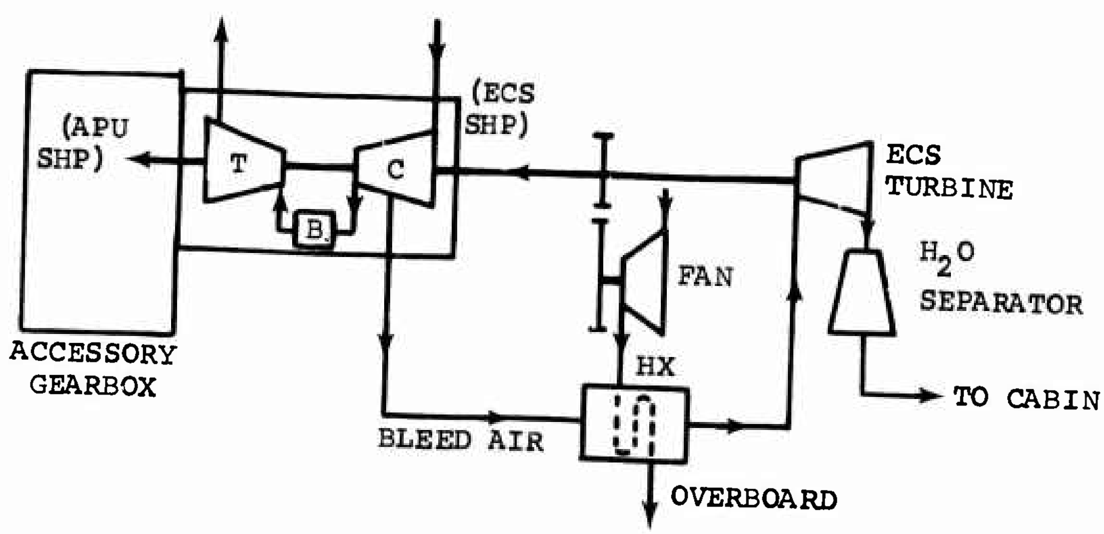

Figure 141. Coupled APU/ECS Approach.

In the coupled approach (Figure 141), the expansion turbine is mounted on either the accessory drive gearbox or the APU gearbox. The heat exchanger fan is mounted separately on the same gearbox. This approach allows both components to rotate at the most efficient speed. The net power returned to the system is the difference between the expansion turbine horsepower and that required to drive the fan. This power supplements that supplied by the APU or main engine and results in an overall fuel saving.

At the sea-level, 130°F day design-point, 35.3 percent of the bleed-air horsepower (12.18 hp) is returned to the system for a Technology Level II System. For Technology Level III, 39.3 percent (10.8 hp) is returned. This means that the APU design-point shaft horsepower levels can be reduced by these amounts. This results in a smaller and lighter APU and also a net fuel saving. However, part of the benefit is offset by the additional weight and volume of the accessory drive gearbox.

Table LVIII summarizes the TOGW penalty decrease for the coupled APU/ECS concept. In the analysis, the APU and starting system weight and volume were decreased by reducing the APU design shaft power by the amount of power returned to the system by the expansion turbine. The accessory drive gearbox was increased by 10 lb and 0.2 ft^3 for Technology Level II and 8 lb and 0.18 ft^3 for Technology Level III.

TABLE LVIII. APU/ECS TOGW PENALTY COMPARISON, SYSTEM 2.4.0.1

System	Technology Level II Standard	Technology Level II Coupled	Technology Level III Standard	Technology Level III Coupled
Without ECS	1185	-	991	-
With ECS (ground use only)	1523	1404	1191	1128
With ECS (APU used in flight to supply ECS bleed air)	1645	1512	1279	1213

Table LVIII shows that a 119-lb TOGW savings can be realized by using the coupled APU/ECS on the ground only for Technology Level II. For Technology Level III, a 63-lb advantage may be realized. For systems utilizing the APU in flight to supply bleed air for the ECS, 133- and 66-lb savings in TOGW may be realized for Technology Levels II and III, respectively. These preliminary figures prove that the concept could be beneficial to this application.

9. REDUNDANT MAIN ENGINE STARTING SYSTEMS

The redundant main engine starting system defined for this study is used in an emergency, independent of the APU. It is a self-contained system capable of starting the main engine under the same conditions at which the primary starting system must function, but not necessarily within the starting time specified for the primary system.

Several basic types of starting systems were analyzed to determine applicability to the recommended system:

1. Hydraulic (accumulator)
2. Electric (battery)
3. Pneumatic (air bottle)
4. Cartridge
5. Cartridge Compressor
6. Jet Fuel Starter

The total weights and volumes of these systems are compared in Table LIX. The systems were sized to provide one start for one engine. Since the primary starting system employs pneumatic starters, the second engine is started by cross-bleeding from the operating engine to the air turbine starter on the second engine.

9.1 HYDRAULIC SYSTEM

The hydraulic system was extremely heavy, due to the large (8000 in.^{3}) accumulator. This system was sized for one start at -65°F ambient conditions, by a comprehensive AiResearch hydraulic starting system computer program, which incorporated the use of empirical data from actual starting systems. Due to the large weight and size, the hydraulic system was judged impractical.

9.2 ELECTRIC SYSTEM

The electric starting system was also one of the heavier systems. This was due primarily to the requirement for two 34-amp-hr nickel-cadmium batteries and a battery heater. Some type of heater would be required to raise the battery electrolyte temperature, if soaked at -65°F, to approximately 0°F or higher, to obtain acceptable performance. The analysis was conducted by matching starter motor performance to battery characteristics at various electrolyte temperatures.

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TABLE LIX. REDUNDANT MAIN ENGINE STARTING SYSTEMS

	Hydraulic Accumulator			Battery			Air Bottle			Cartridge			Cartridge Compressor			JFS		
Technology Level	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
Weight, lb																		
Start motor	16	15	-	26	25.5	23	3**	3**	2**	16	15	13	-	-	-	35.5	30	27
Energy source																		
Hyd accum, 8000 $in.^3$	1360	785	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Battery, 2 - 34 amp-hr	-	-	160	160	152	122	-	-	-	-	-	-	-	-	-	-	-	-
Air bottle, 1380 $in.^3$	-	-	-	-	-	-	49.5	49.5	47.5	-	-	-	-	-	-	-	-	-
Cartridge, including hardware weight	-	-	-	-	-	-	-	-	-	2.5	2.5	2.5	11	11	11	-	-	-
Cartridge compressor	-	-	-	-	-	-	-	-	-	-	-	-	60	58	55	-	-	-
JFS hydraulic start system	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	26	25	22
JFS fuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.5	0.5	0.5
System components (lines, valves, ducts, wiring, control elements, mounts, etc.)	28	28	-	43*	40	25	12	11.5	11	5	5	4.5	6	6	5	10	9.5	8
Engine gearbox pad addition	8	8	-	8.5	8.5	8.5	-	-	-	8	8	8	-	-	-	9	9	9
Total weight, lb	1412	836	-	237.5	226.0	179.5	64	63	60.5	31.5	30.5	27.0	77	75	71	81	74	61.5
Total volume, ft^3	7.5	-	-	2.3	2.3	2.0	0.87	0.87	0.86	0.23	0.23	0.21	0.47	0.47	0.43	0.53	0.5	0.44

*Includes battery heater, 30 lb.
**Addition to ATS for integration of high- and low-pressure system.

9.3 CARTRIDGE SYSTEM

The cartridge starter system has the lowest weight and volume of all systems. This starter unit consists of a cartridge breech assembly, a plenum for cartridge gas nozzles, a turbine wheel, speed reduction gear system, and housing. The cartridge starter is mounted on an engine starter pad, which would be in addition to the air turbine starter pad. Integration of the air turbine and cartridge gas turbine wheels may be accomplished at the expense of compromising efficiency, due to the large variation in nozzle and wheel sizes required. To preserve optimum performance of the primary starting system, a separate cartridge starter was used in this analysis.

The cartridge propellant size required to produce a start was approximately 2 lb, based on ammonium nitrate propellant performance characteristics in existing cartridges. Although this is not a standard size in military inventories, repackaging a standard propellant for optimum mass flow and burn time would be feasible. The drawbacks to cartridges are their storage and logistic support requirements. The weight of this system, including mounts, exhaust duct, and one cartridge, is on the order of 27 to 32 lb, depending on the technology level. Starters of this type are in current use.

The cartridge compressor system, although heavier than the cartridge starter system, offers some distinct advantages, the principal of which is the primary pneumatic starting system without modification. The unit is simply a cartridge-driven compressor that would supply air to the primary system. It is similar to the cartridge starter, except the turbine drives a small centrifugal compressor. Controls are minimal, since the turbine wheel speed is controlled by the compressor load. A pressure relief plug prevents abnormal cartridge overpressure in the breech assembly.

Another advantage of the cartridge compressor is that it may be mounted in the aircraft in more indirect association with the main engine. As such, it is more readily interchangeable, installable as a kit, or could be removed for use on other aircraft. Cartridges may be ignited by dc voltage from an aircraft battery, a small hand generator, or even flashlight batteries. Cartridge compressors of this type have been developed. The total system weight, including a cartridge, is 71 to 77 lb.

9.4 AIR BOTTLE SYSTEM

The air-bottle system weights shown in Table LIX are for a single start at -65°F, with a nominal charge pressure of 3000 psi. The weights represent incremental increases to the air turbine starter in the primary starting system to integrate the high- and low-pressure systems. In operation, the pressure is automatically regulated to 500 psi by a regulator at the bottle.

A source of high-pressure air would be required for recharging or periodically maintaining the bottle pressure. This could be accomplished with a small on-board compressor driven by the main transmission or accessory gearbox. The most probable source would be a ground-operated compressor or high-pressure bottle system. Therefore, the system was not penalized for the recharge equipment; however, this logistical support would have to be provided. The safety and protection of personnel and the aircraft, due to the vulnerability of the high-pressure bottle to battle damage, must be considered with this system. The tabulated system weight of 60.5 to 64 lb would be increased by the addition of containment of protective material.

9.5 JET FUEL STARTER

The jet fuel starter (JFS) is a small free-, gas-turbine engine consisting of a gas generator, accessory, and power sections. The starter is self-sufficient, having its own control and lubrication systems, and performs the starting automatically. The JFS uses the same fuel as the main propulsion engines.

A small, permanent magnet-type generator can be incorporated in the unit to provide electrical power for ignition, or dc power may be used, if available, from an on-board battery. A hydraulic accumulator starting system, similar to the APU system, was included.

The JFS is installed on one of the main engines and requires an additional starter pad. Due to the difference in size between the JFS power turbine and the air turbine starters, the integration of the two functions into a single turbine would seriously compromise the primary system performance and increase the APU size in the primary system.

An advantage of the JFS is the use of main engine fuel; thus, the system does not require additional logistical support. Existing jet fuel starters are not available in the small power class. Existing types are on the order of a 100-hp size.

9.6 SUMMARY

The applicable redundant starting systems were reduced from six to four by elimination of the hydraulic and electric systems on a weight basis. Of the remaining types, the cartridge starter offers by far the lightest component weight--approximately 30 lb. The air-bottle system is next in component weight at about 63 lb, followed by the cartridge compressor at 71 to 77 lb, and the jet fuel starter system at 60 to 81 lb. These are component weights plus the weight of lines, valves, ducting, wiring, mounts, etc. Therefore, installation factors should be on the order of 1.1 to 1.2. Since the redundant starting system would normally be carried as a fixed weight, the increment of TOGW can be determined by multiplying the installed weight by the fixed-weight penalty factor of 2.6. The ΔTOGW penalty for a system would then be on the order of three times the total system component weight.

There are obviously many factors beyond the scope of this study that could influence the selection of the system. Each could be adapted to the recommended SPS 2.4.0.1. One possible factor may be that an additional starter pad could not be provided or would be undesirable. In this case, the air bottle and cartridge compressor systems would be applicable, since both use the same air turbine starter (with modifications for the air-bottle system). The cartridge compressor appears to be the most easily adaptable for several reasons: it is a separately mounted component, the compressed air output is similar to the primary starting system, and it is adaptable as a kit. Logistical support of cartridges would be required. The air-bottle system also requires ground support equipment for recharging, with the potential hazards of a high-pressure system. The JFS, on the other hand, has the same support requirements as other components on the aircraft and uses main engine fuel.

Other considerations may be made when complete self-sufficiency of the aircraft redundant starting system is not imposed. For example, a "buddy system", wherein one aircraft supplies power to the starting system of another, would be quite feasible with the recommended primary starting system. Any aircraft, with the main engine operating, becomes a source of bleed air, which could be ducted by means of an interconnecting hose between aircraft. The pneumatic system within the aircraft would require the addition of an internal duct connection to a hose adapter. The required hose size would be slightly larger than the starter duct inlet, to minimize pressure loss.

10. REQUIRED RESEARCH AND DEVELOPMENT

Technological advancements will be required to achieve the predicted weights, sizes, and performance of the system components for the advanced technology levels. Although some items must be initiated prior to others, no relative priority can be established for the individual tasks, since the successful completion of all is required to achieve the predicted weight, size, and performance of the system.

The man-hours and total cost required to develop the hardware for the advanced technology levels are given on Table LX. The numbers given for Technology Level III are estimates in addition to those for Technology Level II, since the table is based on the premise that 1975 production will be required. Where two numbers are shown, the first is considered for the highest risk approach and the second for the lowest.

10.1 APU

The R&D work outlined in this section summarizes the effort necessary to attain the advanced technology levels in the design of Technology II and III APU. Since the overall configuration of the Technology II APU is similar to that of III most of the tasks are applicable to both levels. The major difference is that the Technology III tasks would be conducted for smaller components with higher pressure ratios, temperatures, and speeds.

10.1.1 Task 1 - Auxiliary Power Unit Design Phase

Objective

Establish a detailed design layout configuration of the APU with attendant gearbox, controls, and accessories.

Approach

1. From established design-point cycle(s) and flow path analyses, perform design analyses in sufficient detail to support thorough design layout. This should include, but not be limited to:

    a. Detailed component definition

    b. Thermal analysis

    c. Mechanical/structural analysis

    d. Critical speed analyses

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TABLE LX. REQUIRED R&D MAN-HOURS AND COST

Research and Development	Technology Level II Man-hours	Technology Level II Total Cost ($1000)	Technology Level III Man-hours	Technology Level III Total Cost ($1000)
APU				
Design Phase	11,000-14,000	200-250	11,000-14,000	200.250
Compressor	4,000- 7,200	210-270	3,200- 4,800	140-180
Combustor	3,250- 5,000	175-250	3,250- 5,000	175-250
Turbine	7,200- 8,400	300-390	4,800- 5,600	200-260
Bearings	2,800- 4,000	100-200	4,200- 6,000	150-300
Structures and Manufacturing	5,000- 6,000	200-325	5,000- 6,000	200-325
Controls	10,500-14,000	385-360	3,200- 6,400	120-240
Gearbox and Fluid Coupling	4,800- 9,600	180-360	3,200- 6,400	120-240
ATS				
Design and Development	14,000	425	10,000	300
ECS				
Design and Development	2,800	90	1,200	40

2. Perform sufficient design layout effort to establish component/structural configuration and integration based upon the modular design approach (i.e., design each major component section as a module integrated within a basic unit main frame).

3. Perform dimensional stackup of entire unit in detail and with each component module related to the main frame.

Justification

Prior to initiating detailed component R&D tasks, the basic unit should be defined in sufficient detail that all work performed will be directly relevant to the end item. This is especially true if the unit is to be designed around the main frame modular approach, wherein the basic unit is comprised of major component modules tied together by a total main frame. The layout will be continuously updated per the results of the individual component tasks.

10.1.2 Task 2 - Compressor

Objective

Based upon the recommended APU configurations, develop a small centrifugal compressor having high efficiency and good range, with the final configuration oriented toward low cost.

Approach

1. Scale the impeller aerodynamics from the smallest applicable compressor wheel, taking into account all design parameters affected by the change in size. Modify design as required for optimum theoretical efficiency.

2. Design a diffusion system that is consistent with the objectives and will minimize the overall diameter. Consider acoustics in blade number and spacing.

3. Consider the use of molded composite materials for compressor end structure, impeller shroud, and diffusion system assemblies. Design parts for abradable shrouds to enable the compressor to operate with minimum clearances.

4. Investigate and develop optimum means of inlet air filtration for minimum noise, pressure drop, and weight.

5. Fabricate a compressor module of the APU as a test rig entity.

6. Test compressor and subcomponents as follows:

   a. Map compressor rotor with vaneless diffuser.

   b. Test rotor with radial diffuser; establish final rotor cutback and diffuser match.

   c. Test with full stage; rotor, radial diffuser, axial vanes and match with turbine stage performance.

   d. Test durability and rub tolerance of compressor face shroud.

7. Perform design modifications, as required to achieve goals commensurate with the recommended APU configuration; uprate the pressure ratio as the task proceeds.

Justification

Overall high compressor performance in the size class, coupled with low-cost objectives, has not yet been demonstrated. The compressor component effort, as summarized, is required to achieve the overall APU and system performance prerequisite of beneficial application to self-sufficient rotary-wing secondary power systems.

10.1.3 Task 3 - Combustor

Objective

Develop an optimum combustor/injector configuration that will minimize cooling, size, and weight without compromising long-life and low-cost objectives.

Approach

1. Investigate various combustor configurations (single-can, reverse-flow annular, etc.) to determine the optimum for this small-size class. Consider fuel injection, high-altitude light-off, contamination, life, etc., in the design objectives.

2. Determine the best liner material that will minimize cooling and still retain long life. Investigate the possibility of combining the turbine stator with combustor, which will enable the stator cooling flow to be used as dilution air in the combustor.

3. Design optimized combustor, subject to the results of the development from Items 1 and 2 above; consider minimizing pressure drop, pattern factor, exhaust emission, and low-frequency combustor noise.

4. Test and develop combustor configuration for the following parameters:

   a. Efficiency and pressure drop

   b. Light-off characteristics

   c. Pattern factor and exhaust emission

   d. Life/endurance/vibration

   e. Sensitivity to contamination

   f. Acoustics

Justification

The development of an advanced technology combustor is justified for the following reasons:

1. Cooling and altitude light-off are problems characteristic of small high-temperature combustors. The high surface-to-volume ratios in small combustors make cooling difficult. Reductions in the cooling requirements by high-temperature materials and possible ceramic coatings will make more air available for dilution essential cooling in the primary liner zone, and will increase the liner life.

2. Low fuel flows cause contamination problems with small orifices, which can easily become clogged. The low fuel flows also make high-altitude starting difficult.

3. Minimizing pressure drops and maximizing the efficiency will decrease the cycle SFC and increase the specific horsepower.

4. Returning turbine stator cooling air to the combustor will reduce the cooling flow penalty to the cycle.

5. Minimizing the pattern factor will increase the life of the turbine stator, turbine wheel, and combustor liner.

6. Designing the combustor for low emission and noise levels will reduce environmental pollution.

10.1.4 Task 4 - Turbine

Objective

Design and develop a small high-work, -speed, and -temperature radial turbine to a life objective commensurate with APU design.

Approach

1. Radial turbine for this application will be scaled from an existing high-work turbine. The blade number must be optimized, considering aerodynamic performance as well as cooling and disk stress design.

2. Cooling schemes for the rotor must be investigated to determine the best method for this size class. The turbine stator cooling design will be coordinated with the combustor development to allow the stator cooling air to be returned to the combustor.

3. The turbine materials will be evaluated with the cooling schemes to ensure adequate turbine life. Consideration will be given to stator materials that do not require cooling, such as silicon nitride or columbium.

4. The turbine module (stator, wheel, and shroud) will be tested over the complete operating range, to verify the design with respect to efficiency, mechanical integrity, cooling effectiveness, and durability.

Justification

The development of an advanced technology turbine is justified for the following reasons:

1. The radial turbine will be one of the critical components affecting the life of the APU. The

effectiveness of the cooling and the mechanical design of the turbine will affect the life of the turbine.

2. The cooling scheme must minimize the cycle penalty for the cooling air, to maintain high specific powers and low SFC's. The radial turbine efficiency will also affect these parameters.

10.1.5 Task 5 - Bearings

Objective

Design and develop foil gas bearings for the APU with the ultimate goal of replacing all rolling contact bearings in the APU (not gearbox) design.

Approach

1. Since the Technology Level II APU requires a single antifriction thrust bearing and a seal, select or design a unit that is capable of high rotational speeds and still meets the life requirements of the APU.

2. Design and develop foil gas bearings for radial and thrust load capability. The bearings must be able to operate at the elevated temperatures within the APU and also at the altitude ceiling of the helicopter. Place particular attention on the selection and development of materials for the bearings, to ensure high-temperature capability and to prevent bearing damage (galling) during an APU shutdown.

3. Construct a dynamic simulator with identical masses and shaft dynamics. The gas bearings would be located, as necessary, to maintain the rotating assembly within allowable limits under all operating conditions. Pressures and temperatures expected in the bearing areas would be simulated as accurately as possible. Starts and operation under known transients and load points would be accomplished, to ascertain that an acceptable design has been generated.

Justification

One of the most common failures in the present-dav APU occurs in the rolling contact bearings. Foil gas bearings can be designed to yield long lives in conjunction with high reliability and reduced maintenance. In addition to the life problems of conventional bearings, oil lubrication systems for the bearings require sealing, pumping, scavenging, bulk storing, defoaming, and cooling for proper performance. Foil gas bearings can eliminate all of these requirements if properlv integrated into an APU.

10.1.6 Task 6 - Structures and Manufacturing Techniques

Objective

Design the structure and develop the manufacturing techniques that will enable the APU to meet the size and performance objectives.

Approach

1. Develop manufacturing techniques for the production of small turbomachinerv at low cost and still maintain the accuracy required to meet the performance goals. Consider integral rotor casting, electrochemical machining of integral rotors, inertia welding of rotating parts, advanced casting techniques, etc.

2. Design the structure to minimize overall weight and reduce rotating component clearance variation caused by thermal excursions of the shrouds/structure. Investigate molded composites in areas such as containment, compressor shrouds, structural members, etc., to reduce weight and thermal expansion. Consider the design of the structure, to ensure a high degree of reliabilitv and ease of maintenance.

3. Fabricate components and test for accuracv, durabilitv, etc.

Justification

The development of advanced technology structures and techniques is justified for the following reasons:

1. Present techniques of manufacturing APU components will not yield the required accuracy for performance with the desirable low cost that high-volume production requires. Further difficulties will be encountered in the small size of the components being considered, in that passage widths and clearances will approach the minimum size of the machining cutters and tools. New techniques must be developed to overcome these problems.

2. The size, weight, and performance goals of the APU necessitate careful structural design. Careful control of clearances will maintain component efficiencies at the levels required by the performance goals. Molded composites in the structure will reduce the overall APU weight.

10.1.7 Task 7 - Controls

Objective

Design and develop a fuel control system for the small, high-speed APU, utilizing electronics and/or fluidics.

Approach

1. Investigate various combinations of electronics and fluidics to arrive at an optimum control system. Objectives of the design will be minimum weight and volume, with high reliability and improved maintainability.

2. Investigate and develop means of turbine inlet temperature sensing, and integrate this concept into the control system package.

3. Design and develop high-speed fuel pump/control for integration into the control system.

4. Fabricate the control system and bench test to determine parameters such as response, system drift, etc.

Justification

The development of advanced technology fuel controls is justified for the following reasons:

1. The cost and complexity of hydromechanical fuel controls can be reduced by incorporating an electronic and/or fluidic fuel control. Less moving parts improve the reliability and maintainability of the control system. The size and weight of an electronic and/or fluidic control system is less than that of a hydrochemical system.

2. A reliable turbine inlet temperature sensor will improve the overall response and accuracy of the control system and provide a much safer overtemperature protection. With the conventional exhaust gas temperature detection, the temperature limit is set by the minimum allowable tailpipe temperature limit. This restricts the maximum power output of the APU at conditions other than the tail-pipe set-point.

3. A higher speed fuel pump/control will reduce not only the size of the pump but the amount of reduction gearing.

10.1.8 Task 8 - Gearbox, Fluid Coupling

Objective

Minimize size and weight of the APU gearbox, fluid coupling.

Approach

1. Investigate and develop techniques for reducing the gearbox size and weight by integrating bearing inner races with gear shafts, using journal bearings, developing co-extruded gears for desired hub and teeth properties, and improving cooling/lubrication techniques to permit higher pitch-line velocities. Use composite materials in conjunction with metal frame for gearbox construction.

2. Design and develop a high-speed fluid coupling for disconnecting the APU from the accessory gearbox. Investigate fluid coupling fabrication, cavitation, filling, draining, and cooling in the design and test phases.

3. Fabricate and test the gearbox as a separate module for determining the following parameters:

   a. Efficiency of the gearbox

b. Vibration characteristics and mechanical integrity

c. Verification of fluid coupling design for efficiency, fill and drain mechanism, and cooling scheme

Justification

The development of an advanced gearbox and fluid coupling is justified for the following reasons:

1. For turbomachinery in this size class, part of the size and weight advantage gained in increasing cycle pressure ratio and turbine inlet temperature is lost by the increased gear reductions imposed by the higher operating speeds. The gearbox weight and volume can be decreased by higher speed accessories (fuel pump, starter, and fluid coupling) and composites in the gearbox case, where possible. Weight savings can be realized by improving bearing arrangements and gear materials.

2. A high-speed fluid coupling, for disconnecting the APU from the accessory gearbox, will minimize the weight penalty for a decoupling device. The high rotational speeds possible with a fluid coupling will also reduce the amount of gear reduction.

10.2 AIR TURBINE STARTER

Objective

Design and develop an optimized air turbine starter.

Approach

It is recommended that a development program be conducted on the complete starter unit, using the prototype model as the test device. Since the turbine and the speed reduction gearbox are the principal units involved in the technological advancement tasks, testing is interrelated, and the complete rotating assembly can be more conveniently tested as a single unit.

The predicted weight and size of the air turbine starter is dependent upon development of a small, high-speed, efficient turbine. A turbine wheel diameter of 2 in. would be required.

Both axial- and radial-flow turbines should be investigated for the highest efficiency for this small size. The aerodynamic design of the turbine will require optimizing the wheel, nozzle, inlet, and exhaust diffuser. Careful attention to running clearances must be given to obtain maximum efficiency. Turbine material selection must be compatible with turbine environment and starter life requirements.

For the speed reduction gearing, the system efficiency can be improved by reducing gear pumping losses. The conventional splash method of lubrication produces these losses from the gears, which operate partially submerged in an oil sump. Shrouded gears, thin gear sections, positive oil supply, and low oil level can minimize such losses. Attention must also be directed in the design to higher speed, low friction bearings and seals.

A starter cutout switch and an overrunning device at the output shaft are also required in the complete design.

The program for a Technology Level II production time would be conducted in two phases. The initial phase would consist of the design, fabrication, and testing of a prototype unit that would require approximately 17 months, at which time one or more prototype units could be available. This development testing should be sufficient to ensure performance design goals (including simulated duty cycles) and overall integrity of the design.

The second phase, requiring 8 months, would consist of the design, fabrication, and qualification testing of the starter. Finalized design would be based on the results of Phase I. Testing would consist of such items as endurance operation, which includes start cycles and overrunning, simulated duty cycles, running engagements, vibrations, and hot and colt tests.

The program for a Technology Level III production period would require optimization of the turbine and associated gear system for the higher bleed-air pressure levels available. The lower weight of this starter will require additional materials (such as boron composities for major structural parts) to increase strength-to-weight factors. Further optimization of the lubrication system may be attained by using air to lubricate and cool bearings and gears. This program will require approximately 26 months.

Justification

Air turbine starters in the small power class are not currently available. The scaling of existing, larger sizes will not produce the performance, weight, and size needed. Therefore, a new starter unit is required to meet the predicted parameters.

10.3 ENVIRONMENTAL CONTROL SYSTEM

Performance and Component Optimization

Objective

Develop an advanced technology air cycle ECS by measurably reducing the total bleed-air required for cooling and, subsequently, reducing component size and weight.

Approach

An air cycle ECS that incorporates a reheat-condenser and a cabin air recirculation system offers a potential performance improvement and a smaller component size than conventional air cycle systems. Specifically, the design goals for a system of this type are to:

1. Minimize free moisture at the turbine inlet.

2. Eliminate icing problems at the turbine discharge.

3. Reduce total bleed-airflow required for a given capacity, by recycling a portion of cabin air and mixing with turbine air in an ejector.

4. Eliminate the filter-type water separator, by incorporating a reheat-condenser heat exchanger in conjunction with a cabin recirculating system.

Many variations to the simple air cycle system have been utilized, including reheat-condensers. However, the design of a system of this type to operate in conjunction with the recirculated cabin air will involve optimization of the entire system for the specific bleed-air conditions available.

The goal of the program is to demonstrate the performance advantage of the reheat-condenser plus recirculation system, compared to a conventional simple-cycle system. Both systems would be optimized for the same supply air pressure ratio and

cooling capacity. The results will compare the cooling capacity at off-design points, the amount of moisture in the cabin supply, component weights, and total bleed air required.

This program would be composed of the following phases:

1. Phase I is the sizing of components for the reheat-condenser, cabin recirculation system and a conventional system using analytical and laboratory techniques. Existing hardware is to be used whereever possible.

2. Phase II is the final development of the reheat-condenser, cabin recirculation system. The development will optimize the jet pump configuration to ensure the proper airflow through the reheat-condenser and the recirculated cabin air duct.

3. Phase III is the testing of the conventional system for comparison with the Phase II test results.

The design of the jet pump will be critical to the system performance and will require special design attention. In operation, the jet pump back-pressures the cooling turbine to obtain enough energy to recirculate cabin air and regenerative air. This degrades the turbine performance unless the supply pressure can be maintained sufficiently high to accomplish the required delta temperature in the turbine and at the same time have sufficient discharge pressure to operate the jet pump. Development, may, however. dictate two separate jet pumps, in series, with the second jet pump slightly downstream from the reheat-condenser air ejector. The location of the jet pump is critical and is finalized by testing in the laboratory to substantiate performance and determine the most optimum position. Optimizing the cabin recirculating flow with respect to turbine flow will be part of this development.

To achieve the weights predicted for the advanced technology systems, materials and fabrication advancements will be required. The specific areas of development are:

1. Nonmetallic materials for structural and ducting applications

2. Assembly and bonding techniques of nonmetallic components to metallic components

3. Lightweight containment shrouds of materials such as honeycomb sandwich

4. New brazing alloys and techniques for fabricating a titanium-alloy heat exchanger

Justification

The reduction in bleed air for the cooling system will directly result in reduced APU size and reduced engine penalties for bleed-air extraction throughout the aircraft mission. Systems with ECS will require an APU sized for the ECS bleed flow, whereas systems without ECS, will have an APU sized for engine starting. However, with advancing technology, the difference in bleed-air requirements of the ECS and engine starter will decrease to the point where little or no penalty in bleed-air extraction from the APU or main engine will occur. Thus, both the fixed and expendable weight penalties to the aircraft, resulting from ECS installation, will be materially reduced.

Lighter weight materials are required to achieve component weight reductions in advanced systems. Although some nonmetallic materials are in production and some are being developed, further reductions in weight are predicted through the use of these materials for advanced systems.

Aluminum heat exchangers, although compatible with current and short-term advancements in aircraft systems, will not be compatible with the higher bleed-air temperatures associated with advanced engines and the APU. The alternative to developing advanced heat exchanger material technology is to install a conventional stainless steel precooler in series (upstream) with the ECS heat exchanger; this will add weight and complexity to the overall aircraft.

APPENDIX I
SYSTEM EVALUATIONS

TECHNOLOGY LEVEL I

TABLE LXI:

SYSTEM TITLE	WEIGHTED PERCENT SPS IMPROVEMENT
SYSTEM 1.1.0.1 I. WITHOUT ECS	-13.931
SYSTEM 1.2.0.1 I. WITHOUT ECS	-13.085
SYSTEM 1.4.1.0. I. WITHOUT ECS	-7.645
SYSTEM 2.4.1.0. I. WITHOUT ECS	-6.892
SYSTEM 1.4.0.1. I. WITHOUT ECS	.000
SYSTEM 2.4.0.1. I. WITHOUT ECS	.217

TABLE LXII:

SYSTEM 1.4.1.0. I. WITH ECS	-5.210
SYSTEM 2.4.1.0. I. WITH ECS	-4.375
SYSTEM 1.4.2.0. I. WITH ECS	-2.510
SYSTEM 2.4.2.0. I. WITH ECS	-1.799
SYSTEM 1.4.0.1. I. WITH ECS	.000
SYSTEM 2.4.0.1. I. WITH ECS	.699

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TABLE LXI. SYSTEMS WITHOUT ECS

SYSTEM 1.1.0.1 I. WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	16.50	1.05	.40
PUMP FLT CTL	13.50	1.05	.36
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
ATM ADG	27.00	1.05	.10
2-ATS ENG	14.00	1.05	.10
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	14.00	1.10	.26
ACC DRIVE G/B	49.00	1.25	1.43
APU	72.00	1.00	1.21
APU STRT SYS	67.92	1.25	.51
OIL COOLING SYS	10.00	1.25	.16

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	0.0	0.0	27.6	54.3	APU	14.1 LB
HYD CHECKOUT	.250	0.	130.0	0.0	0.0	21.6	42.5	APU	12.5 LB
MAIN ENG1 START	.008	0.	130.0	0.0	0.0	28.7	54.5	APU	.5 LB
MAIN ENG2 START	.008	0.	130.0	0.0	0.0	28.7	54.5	APU	.5 LB
STANDBY	.083	0.	130.0	34.5	0.0	0.0	0.0	ME	3.0 LB
CRUISE	1.000	4000.	95.0	34.0	0.0	0.0	0.0	ME	56.1 LB

TOTAL SPS INST. WT. 520.56 LB. SPS INST. WT. PENALTY 1376.48 LB. SPS EXPENDABLE WT. PENALTY 182.01 LB.

TOTAL SPS INST. VOL. 5.84 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	350.86 LB	60.40	-1	-16.85	.10	-1.685
SYSTEM VOLUME	5.06 CU FT	.78	-1	-15.42	.05	-.771
TOGW PENALTY	1336.59 LB	219.89	-1	-16.45	.40	-6.581
RELIABILITY-MTBF	414.00 HRS	-32.00	-1	-7.73	.10	-.77
MAINTAINABILITY-MMH/FH	.088	.001	-1	-1.14	.05	-.057
AVAILABILITY	99.23	-.07	-1	-.07	.05	-.004
SYSTEM VULNERABILITY	100.00	8.00	-1	-8.00	.02	-.160
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	9.00	-1	-9.00	.05	-.450
LIFE CYCLE COST	100.00	25.01	-1	-25.01	.13	-3.251

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -13.931

TABLE LXI - Continued

SYSTEM 1.2.0.1 I. WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	19.50	1.05	.49
PUMP FLT CTL	13.50	1.05	.36
PUMP APU	9.00	1.05	.05
MOTOR ADG	7.60	1.05	.03
SYS COMPONENTS-H	4.00	1.10	.02
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
2-ATS ENG	14.00	1.05	.10
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	13.00	1.10	.22
ACC DRIVE G/B	49.00	1.25	1.40
APU	68.10	1.80	1.01
APU STRT SYS	67.49	1.25	.50
OIL COOLING SYS	18.00	1.25	.26

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	47.7	0.0	-0.0	47.7	APU	13.3 LB
HYD CHECKOUT	.250	0.	130.0	20.5	0.0	0.0	20.5	APU	10.0 LB
MAIN ENG1 START	.008	0.	130.0	27.7	0.0	14.5	56.2	APU	.5 LB
MAIN ENG2 START	.008	0.	130.0	27.7	0.0	14.5	56.2	APU	.5 LB
STANDBY	.083	0.	130.0	36.5	0.0	0.0	0.0	ME	3.0 LB
CRUISE	3.000	4000.	95.0	34.0	0.0	0.0	0.0	ME	56.1 LB

TOTAL SPS INST. WT. 525.00 LB. SPS INST. WT. PENALTY 1364.99 LB. SPS EXPENDABLE WT. PENALTY 175.14 LB.
TOTAL SPS INST. VOL. 5.70 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	358.84 LB	58.85	-1	-16.40	.10	-1.640
SYSTEM VOLUME	5.06 CU FT	.64	-1	-12.65	.05	-.632
TOGW PENALTY	1336.59 LB	203.54	-1	-15.23	.40	-6.091
RELIABILITY-MTBF	414.00 HRS	-40.00	+1	-9.66	.10	-.97
MAINTAINABILITY-MMH/FH	.088	.011	-1	-12.50	.05	-.625
AVAILABILITY	99.23	-.20	+1	-.20	.05	-.010
SYSTEM VULNERABILITY	100.00	18.00	-1	-18.00	.02	-.360
AIRCRAFT COMPLEXITY	100.00	10.00	-1	-10.00	.05	-.500
SPS COMPLEXITY	100.00	18.00	-1	-18.00	.05	-.900
LIFE CYCLE COST	100.00	10.46	-1	-10.46	.13	-1.360

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -13.085

TABLE LXI - Continued

SYSTEM 1.4.1.0, I, WITHOUT FCS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	16.50	1.05	.48
PUMP FLT CTL	13.50	1.05	.36
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
COMPRESSOR ADG	22.40	1.05	.27
2-ATS ENG	14.00	1.05	.10
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	11.00	1.10	.17
ACC DRIVE G/B	53.00	1.25	1.40
APU	59.60	1.80	.69
APU STRT SYS	51.78	1.25	.37
SHAFT-APU TO ADG	3.00	1.00	.05
OIL COOLING SYS	9.00	1.25	.14

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	32.1	0.0	0.0	32.1	APU	10.8 LB
HYD CHECKOUT	.250	0.	130.0	25.2	0.0	0.0	25.2	APU	9.9 LB
MAIN ENG1 START	.008	0.	130.0	45.3	0.0	0.0	45.3	APU	.4 LB
MAIN ENG2 START	.008	0.	130.0	45.3	0.0	0.0	45.3	APU	.4 LB
STANDBY	.083	0.	130.0	36.5	0.0	0.0	0.0	ME	3.0 LB
CRUISE	3.000	4000.	95.0	34.0	0.0	0.0	0.0	ME	56.1 LB

TOTAL SPS INST. WT. 483.15 LB. SPS INST. WT. PENALTY 1256.19 LB. SPS EXPENDABLE WT. PENALTY 169.39 LB.
TOTAL SPS INST. VOL. 5.29 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	358.84 LB	29.44	-1	-8.20	.10	-.820
SYSTEM VOLUME	5.06 CU FT	.23	-1	-4.55	.05	-.227
TOGW PENALTY	1336.59 LB	88.99	-1	-6.66	.40	-2.663
RELIABILITY-MTBF	414.00 HRS	-22.00	+1	-5.31	.10	-.53
MAINTAINABILITY-MMH/FH	.088	.001	-1	-1.14	.05	-.057
AVAILABILITY	99.23	-.10	+1	-.10	.05	-.005
SYSTEM VULNERABILITY	100.00	7.00	-1	-7.00	.02	-.140
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	8.00	-1	-8.00	.05	-.400
LIFE CYCLE COST	100.00	20.01	-1	-20.01	.13	-2.601
SPS TOTAL WEIGHTED PERCENT IMPROVEMENT						-7.645

TABLE LXI - Continued

SYSTEM 2.4.1.0. I. WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	16.50	1.05	.48
PUMP FLT CTL	13.50	1.05	.36
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
COMPRESSOR ADG	22.40	1.05	.27
2-ATS ENG	14.00	1.05	.10
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	11.00	1.10	.17
ACC DRIVE G/B	57.00	1.25	1.50
APU	59.60	1.80	.69
APU STRT SYS	51.78	1.25	.37
OIL COOLING SYS	9.00	1.25	.14

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
FLEC CHECKOUT	.250	0.	130.0	32.1	0.0	0.0	32.1	APU	6.8 LB
HYD CHECKOUT	.250	0.	130.0	25.2	0.0	0.0	25.2	APU	6.8 LB
MAIN ENG1 START	.008	0.	130.0	45.3	0.0	0.0	45.3	APU	.2 LB
MAIN ENG2 START	.008	0.	130.0	45.3	0.0	0.0	45.3	APU	.2 LB
STANDBY	.083	0.	130.0	36.5	0.0	0.0	0.0	ME	3.0 LB
CRUISE	3.000	4000.	95.0	34.0	0.0	0.0	0.0	ME	56.1 LB

TOTAL SPS INST. WT. 485.15 LB. SPS INST. WT. PENALTY 1261.39 LB. SPS EXPENDABLE WT. PENALTY 153.92 LB.
TOTAL SPS INST. VOL. 5.34 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	358.84 LB	30.44	-1	-8.48	.10	-.848
SYSTEM VOLUME	5.06 CU FT	.28	-1	-5.53	.05	-.277
TOGW PENALTY	1336.59 LB	78.72	-1	-5.89	.40	-2.356
RELIABILITY-MTBF	414.00 HRS	-21.00	+1	-5.07	.10	-.51
MAINTAINABILITY-MMH/FH	.088	.002	-1	-2.27	.05	-.114
AVAILABILITY	99.23	-.09	+1	-.09	.05	-.005
SYSTEM VULNERABILITY	100.00	3.00	-1	-3.00	.02	-.060
AIRCRAFT COMPLEXITY	100.00	2.00	-1	-2.00	.05	-.100
SPS COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
LIFE CYCLE COST	100.00	18.66	-1	-18.66	.13	-2.426
SPS TOTAL WEIGHTED PERCENT IMPROVEMENT						-6.892

TABLE LXI - Continued

SYSTEM 1.4.0.1. I. WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	16.50	1.05	.48
PUMP FLT CTL	13.50	1.05	.36
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
2-ATS ENG	14.00	1.05	.10
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS	11.00	1.10	.17
ACC DRIVE G/B	47.00	1.25	1.30
APU	59.00	1.80	.84
APU STRT SYS	51.34	1.25	.36
SHAFT-APU TO ADG	3.00	1.00	.05
OIL COOLING SYS	9.00	1.25	.14

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	32.4	0.0	0.0	32.4	APU	9.8 LB
HYD CHECKOUT	.250	0.	130.0	25.2	0.0	0.0	25.2	APU	9.0 LB
MAIN ENG1 START	.008	0.	130.0	16.5	0.0	14.5	45.0	APU	.4 LB
MAIN ENG2 START	.008	0.	130.0	16.5	0.0	14.5	45.0	APU	.4 LB
STANDBY	.083	0.	130.0	36.5	0.0	0.0	0.0	ME	3.0 LB
CRUISE	3.000	4000.	95.0	34.0	0.0	0.0	0.0	ME	56.1 LB

TOTAL SPS INST. WT. 450.50 LB.
TOTAL SPS INST. VOL. 5.06 CU. FT.

SPS INST. WT. PENALTY 1171.30 LB.

SPS EXPENDABLE WT. PENALTY 165.29 LB.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	358.84 LB	-.00	-1	.00	.10	.000
SYSTEM VOLUME	5.06 CU FT	-.00	-1	.00	.05	.000
TOGW PENALTY	1336.59 LB	-.00	-1	.00	.40	.000
RELIABILITY-MTBF	414.00 HRS	0.00	+1	0.00	.10	0.00
MAINTAINABILITY-MMH/FH	.088	0.000	-1	-0.00	.05	0.000
AVAILABILITY	99.23	0.00	+1	0.00	.05	0.000
SYSTEM VULNERABILITY	100.00	0.00	-1	-0.00	.02	0.000
AIRCRAFT COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
SPS COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
LIFE CYCLE COST	100.00	0.00	-1	-0.00	.13	0.000

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT .000

TABLE LXI - Concluded

SYSTEM 2.4.0.1, I. WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	16.50	1.05	.48
PUMP FLT CTL	13.50	1.05	.36
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
2-ATS ENG	14.00	1.05	.10
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	11.00	1.10	.17
ACC DRIVE G/B	51.00	1.25	1.40
APU	59.00	1.80	.84
APU STRT SYS	51.34	1.25	.36
OIL COOLING SYS	9.00	1.25	.14

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	32.4	0.0	0.0	32.4	APU	9.8 LB
HYD CHECKOUT	.250	0.	130.0	25.2	0.0	0.0	25.2	APU	9.0 LB
MAIN ENG1 START	.008	0.	130.0	16.5	0.0	14.5	45.0	APU	.4 LB
MAIN ENG2 START	.008	0.	130.0	16.5	0.0	14.5	45.0	APU	.4 LB
STANDBY	.083	0.	130.0	36.5	0.0	0.0	0.0	ME	3.0 LB
CRUISE	3.000	4000.	95.0	34.0	0.0	0.0	0.0	ME	56.1 LB

TOTAL SPS INST. WT. 452.50 LB. SPS INST. WT. PENALTY 1176.50 LB. SPS EXPENDABLE WT. PENALTY 165.29 LB.
TOTAL SPS INST. VOL. 5.11 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	358.84 LB	1.00	-1	-.28	.10	-.028
SYSTEM VOLUME	5.06 CU FT	.05	-1	-.99	.05	-.049
TOGW PENALTY	1336.59 LB	5.20	-1	-.39	.40	-.155
RELIABILITY-MTBF	414.00 HRS	1.00	+1	.24	.10	.02
MAINTAINABILITY-MMH/FH	.088	-.001	-1	1.14	.05	.057
AVAILABILITY	99.23	-.02	+1	-.02	.05	-.001
SYSTEM VULNERABILITY	100.00	-4.00	-1	4.00	.02	.080
AIRCRAFT COMPLEXITY	100.00	-2.00	-1	2.00	.05	.100
SPS COMPLEXITY	100.00	-5.00	-1	5.00	.05	.250
LIFE CYCLE COST	100.00	.46	-1	-.46	.13	-.060
SPS TOTAL WEIGHTED PERCENT IMPROVEMENT						.217

TABLE LXII. SYSTEMS WITH ECS

SYSTEM 1.4.1.0, I, WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	16.50	1.05	.48
PUMP FLT CTL	13.50	1.05	.36
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
COMPRESSOR ADG	25.50	1.05	.33
2-ATS ENG	14.00	1.05	.10
ECS	27.00	1.35	1.70
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	11.00	1.10	.17
ACC DRIVE G/B	53.00	1.25	1.40
SHAFT-APU TO ADG	3.00	1.00	.05
APU	80.80	1.80	1.09
APU STRT SYS	104.17	1.25	.82
OIL COOLING SYS	10.00	1.25	.16

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	81.5	0.0	0.0	81.5	APU	18.9 LB
HYD CHECKOUT	.250	0.	130.0	71.1	0.0	0.0	71.1	APU	17.7 LB
MAIN ENG1 START	.008	0.	130.0	46.0	0.0	0.0	46.0	APU	.5 LB
MAIN ENG2 START	.008	0.	130.0	46.0	0.0	0.0	46.0	APU	.5 LB
STANDBY	.083	0.	130.0	36.5	0.0	23.0	0.0	ME	5.7 LB
CRUISE	3.000	4000.	95.0	34.0	0.0	23.0	0.0	ME	152.7 LB

TOTAL SPS INST. WT. 609.53 LB.
TOTAL SPS INST. VOL. 7.73 CU. FT.

SPS INST. WT. PENALTY 1584.77 LB.

SPS EXPENDABLE WT. PENALTY 411.58 LB.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	454.75 LB	24.72	-1	-5.44	.10	-.544
SYSTEM VOLUME	7.77 CU FT	-.04	-1	.51	.05	.026
TOGW PENALTY	1950.[illegible]7 LB	45.49	-1	-2.33	.40	-.933
RELIABILITY-MTBF	361.00 HRS	-16.00	+1	-4.43	.10	-.44
MAINTAINABILITY-MMH/FH	.096	.001	-1	-1.04	.05	-.052
AVAILABILITY	99.06	-.04	+1	-.04	.05	-.002
SYSTEM VULNERABILITY	100.00	7.00	-1	-7.00	.02	-.140
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	9.00	-1	-9.00	.05	-.450
LIFE CYCLE COST	100.00	19.02	-1	-19.02	.13	-2.473

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -5.210

TABLE LXII - Continued

SYSTEM 2.4.1.0, I, WITH ECS

SYSTEM COMPONENTS	WT. LB.	INS. FAC.	VOL.
PUMP UTIL	16.50	1.05	.48
PUMP FLT CTL	13.50	1.05	.36
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
COMPRESSOR ADS	25.50	1.05	.33
2-ATS ENG	14.00	1.05	.10
ECS	27.00	1.35	1.70
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	11.00	1.10	.17
ACC DRIVE G/B	53.00	1.25	1.40
APU	80.80	1.80	1.09
APU STRT SYS	104.17	1.25	.82
OIL COOLING SYS	10.00	1.25	.16

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	81.5	0.0	0.0	81.5	APU	18.9 LB
HYD CHECKOUT	.250	0.	130.0	71.1	0.0	0.0	71.1	APU	17.7 LB
MAIN ENG1 START	.008	0.	130.0	46.0	0.0	0.0	46.0	APU	.5 LB
MAIN ENG2 START	.008	0.	130.0	46.0	0.0	0.0	46.0	APU	.5 LB
STANDBY	.083	0.	130.0	36.5	0.0	23.0	0.0	ME	5.7 LB
CRUISE	3.000	4000.	95.0	34.0	0.0	23.0	0.0	ME	152.7 LB

TOTAL SPS INST. WT. 606.53 LB. SPS INST. WT. PENALTY 1576.97 LB. SPS EXPENDABLE WT. PENALTY 411.58 LB.
TOTAL SPS INST. VOL. 7.69 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	454.75 LB	21.72	-1	-4.78	.10	-.478
SYSTEM VOLUME	7.77 CU FT	-.09	-1	1.16	.05	.058
TOGW PENALTY	1950.87 LB	37.69	-1	-1.93	.40	-.773
RELIABILITY-MTBF	361.00 HRS	-15.00	+1	-4.16	.10	-.42
MAINTAINABILITY-MMH/FH	.096	.002	-1	-2.08	.05	-.104
AVAILABILITY	99.06	-.09	+1	-.09	.05	-.005
SYSTEM VULNERABILITY	100.00	3.00	-1	-3.00	.02	-.060
AIRCRAFT COMPLEXITY	100.00	2.00	-1	-2.00	.05	-.100
SPS COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
LIFE CYCLE COST	100.00	17.68	-1	-17.68	.13	-2.298

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -4.375

TABLE LXII - Continued

SYSTEM 1.4.2.0. I. WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	21.80	1.05	.69
PUMP FLT CTL	13.50	1.05	.36
2-MOTOR ENG STRT	25.60	1.05	.12
SYS COMPONENTS-H	9.90	1.10	.04
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
ECS	27.00	1.35	1.70
VENT FAN	6.00	1.25	.07
ACC DRIVE G/B	47.00	1.25	1.30
SHAFT-APU TO ADG	3.00	1.00	.05
APU	95.30	1.80	1.63
APU STRT SYS	100.69	1.25	.79
OIL COOLING SYS	10.00	1.25	.16

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	33.8	0.0	23.0	79.1	APU	20.1 LB
HYD CHECKOUT	.250	0.	130.0	26.2	0.0	23.0	71.5	APU	19.1 LB
MAIN ENG1 START	.008	0.	130.0	43.9	0.0	0.0	43.9	APU	.5 LB
MAIN ENG2 START	.008	0.	130.0	43.9	0.0	0.0	43.9	APU	.5 LB
STANDBY	.083	0.	130.0	36.5	0.0	23.0	0.0	ME	5.7 LB
CRUISE	3.000	4000.	95.0	34.0	0.0	23.0	0.0	ME	152.7 LB

TOTAL SPS INST. WT. 613.54 LB. SPS INST. WT. PENALTY 1595.20 LB. SPS EXPENDABLE WT. PENALTY 417.26 LB.
TOTAL SPS INST. VOL. 7.91 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	454.75 LB	20.04	-1	-4.41	.10	-.441
SYSTEM VOLUME	7.77 CU FT	.14	-1	-1.80	.05	-.090
TOGW PENALTY	1950.87 LB	61.59	-1	-3.16	.40	-1.263
RELIABILITY-MTBF	361.00 HRS	36.00	+1	9.97	.10	1.00
MAINTAINABILITY-MMH/FH	.096	.009	-1	-9.37	.05	-.469
AVAILABILITY	99.06	-.05	+1	-.05	.05	-.003
SYSTEM VULNERABILITY	100.00	10.00	-1	-10.00	.02	-.200
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	9.00	-1	-9.00	.05	-.450
LIFE CYCLE COST	100.00	3.02	-1	-3.02	.13	-.393
SPS TOTAL WEIGHTED PERCENT IMPROVEMENT						-2.510

TABLE LXII - Continued

SYSTEM 2.4.2.0. I. WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	21.80	1.05	.69
PUMP FLT CTL	13.50	1.05	.36
2-MOTOR ENG STRT	25.60	1.05	.12
SYS COMPONENTS-H	9.90	1.10	.04
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
ECS	27.00	1.35	1.70
VENT FAN	6.00	1.25	.07
ACC DRIVE G/B	47.00	1.25	1.30
APU	95.30	1.80	1.63
APU STRT SYS	100.69	1.25	.79
OIL COOLING SYS	10.00	1.25	.16

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	33.8	0.0	23.0	79.1	APU	20.1 LB
HYD CHECKOUT	.250	0.	130.0	26.2	0.0	23.0	71.5	APU	19.1 LB
MAIN ENG1 START	.008	0.	130.0	43.9	0.0	0.0	43.9	APU	.5 LB
MAIN ENG2 START	.008	0.	130.0	43.9	0.0	0.0	43.9	APU	.5 LB
STANDBY	.083	0.	130.0	36.5	0.0	23.0	0.0	ME	5.7 LB
CRUISE	3.000	4000.	95.0	34.0	0.0	23.0	0.0	ME	152.7 LB

TOTAL SPS INST. WT. 610.54 LB. SPS INST. WT. PENALTY 1587.40 LB. SPS EXPENDABLE WT. PENALTY 417.26 LB.
TOTAL SPS INST. VOL. 7.86 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	454.75 LB	17.04	-1	-3.75	.10	-.375
SYSTEM VOLUME	7.77 CU FT	.09	-1	-1.16	.05	-.058
TOGW PENALTY	1950.87 LB	53.79	-1	-2.76	.40	-1.103
RELIABILITY-MTBF	361.00 HRS	37.00	+1	10.25	.10	1.02
MAINTAINABILITY-MMH/FH	.096	.008	-1	-8.33	.05	-.417
AVAILABILITY	99.06	-.07	+1	-.07	.05	-.004
SYSTEM VULNERABILITY	100.00	6.00	-1	-6.00	.02	-.120
AIRCRAFT COMPLEXITY	100.00	2.00	-1	-2.00	.05	-.100
SPS COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
LIFE CYCLE COST	100.00	3.45	-1	-3.45	.13	-.448

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -1.799

TABLE LXII - Continued

SYSTEM 1.4.0.1. I. WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	16.50	1.05	.48
PUMP FLT CTL	13.50	1.05	.36
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
2-ATS ENG	14.00	1.05	.10
ECS	27.00	1.35	1.70
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	11.00	1.10	.17
ACC DRIVE G/B	47.00	1.25	1.30
SHAFT-APU TO ADG	3.00	1.00	.05
APU	92.80	1.80	1.61
APU STRT SYS	98.95	1.25	.77
OIL COOLING SYS	10.00	1.25	.16

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	32.6	0.0	23.0	77.9	APU	19.8 LB
HYD CHECKOUT	.250	0.	130.0	25.2	0.0	23.0	70.5	APU	18.8 LB
MAIN ENG1 START	.008	0.	130.0	16.3	0.0	13.3	42.5	APU	.5 LB
MAIN ENG2 START	.008	0.	130.0	16.3	0.0	13.3	42.5	APU	.5 LB
STANDBY	.083	0.	130.0	36.5	0.0	23.0	0.0	ME	5.7 LB
CRUISE	3.000	4000.	95.0	34.0	0.0	23.0	0.0	ME	152.7 LB

TOTAL SPS INST. WT. 590.33 LB.   SPS INST. WT. PENALTY 1534.85 LB.   SPS EXPENDABLE WT. PENALTY 416.02 LB.
TOTAL SPS INST. VOL. 7.77 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	454.75 LB	-.00	-1	.00	.10	.000
SYSTEM VOLUME	7.77 CU FT	-.00	-1	.00	.05	.000
TOGW PENALTY	1950.87 LB	-.00	-1	.00	.40	.000
RELIABILITY-MTBF	361.00 HRS	0.00	+1	0.00	.10	0.00
MAINTAINABILITY-MMH/FH	.096	0.000	-1	-0.00	.05	0.000
AVAILABILITY	99.06	0.00	+1	0.00	.05	0.000
SYSTEM VULNERABILITY	100.00	0.00	-1	-0.00	.02	0.000
AIRCRAFT COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
SPS COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
LIFE CYCLE COST	100.00	0.00	-1	-0.00	.13	0.000

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT .000

TABLE LXII - Concluded

SYSTEM 2.4.0.1. I. WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	16.50	1.05	.48
PUMP FLT CTL	13.50	1.05	.36
2-40 KVA GENS	68.00	1.05	.44
SYS COMPONENTS-E	47.00	1.10	.56
2-ATS ENG	14.00	1.05	.10
ECS	27.00	1.35	1.70
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	11.00	1.10	.17
ACC DRIVE G/B	47.00	1.25	1.30
APU	92.90	1.80	1.61
APU STRT SYS	98.95	1.25	.77
OIL COOLING SYS	10.00	1.25	.16

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	32.6	0.0	23.0	77.9	APU	19.8 LB
HYD CHECKOUT	.250	0.	130.0	25.2	0.0	23.0	70.5	APU	18.8 LB
MAIN ENG1 START	.008	0.	130.0	16.3	0.0	13.3	42.5	APU	.5 LB
MAIN ENG2 START	.008	0.	130.0	16.3	0.0	13.3	42.5	APU	.5 LB
STANDBY	.083	0.	130.0	36.5	0.0	23.0	0.0	ME	5.7 LB
CRUISE	3.000	4000.	95.0	34.0	0.0	23.0	0.0	ME	152.7 LB

TOTAL SPS INST. WT. 587.51 LB. SPS INST. WT. PENALTY 1527.52 LB. SPS EXPENDABLE WT. PENALTY 416.02 LB.
TOTAL SPS INST. VOL. 7.72 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	454.75 LB	-2.90	-1	.64	.10	.064
SYSTEM VOLUME	7.77 CU FT	-.05	-1	.64	.05	.032
TOGW PENALTY	1950.87 LB	-7.34	-1	.38	.40	.150
RELIABILITY-MTBF	361.00 HRS	1.00	+1	.28	.10	.03
MAINTAINABILITY-MMH/FH	.096	-.001	-1	1.04	.05	.052
AVAILABILITY	99.06	-.02	+1	-.02	.05	-.001
SYSTEM VULNERABILITY	100.00	-4.00	-1	4.00	.02	.080
AIRCRAFT COMPLEXITY	100.00	-2.00	-1	2.00	.05	.100
SPS COMPLEXITY	100.00	-5.00	-1	5.00	.05	.250
LIFE CYCLE COST	100.00	.43	-1	-.43	.13	-.056

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT .699

TECHNOLOGY LEVEL II

TABLE LXIII:

SYSTEM TITLE	WEIGHTED PERCENT SPS IMPROVEMENT
SYSTEM 1.1.0.1, II, WITHOUT ECS	-13.686
SYSTEM 1.2.0.1, II, WITHOUT ECS	-12.567
SYSTEM 1.4.1.0, II, WITHOUT ECS	-9.142
SYSTEM 2.4.1.0, II, WITHOUT ECS	-8.606
SYSTEM 1.4.0.1, II, WITHOUT ECS	.000
SYSTEM 2.4.0.1, II, WITHOUT ECS	.366

TABLE LXIV:

SYSTEM 1.4.1.0, II, WITH ECS	-7.042
SYSTEM 2.4.1.0, II, WITH ECS	-6.014
SYSTEM 1.4.2.0, II, WITH ECS	-3.133
SYSTEM 2.4.2.0, II, WITH ECS	-1.855
SYSTEM 1.4.0.1, II, WITH ECS	.000
SYSTEM 2.4.0.1, II, WITH ECS	1.366

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TABLE LXIII. SYSTEMS WITHOUT ECS

SYSTEM 1.1.0.1. II. WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.70	1.05	.48
PUMP FLT CTL	13.00	1.05	.36
2-40 KVA GENS	66.00	1.05	.42
SYS COMPONENTS-E	47.00	1.10	.56
ATM ADG	22.00	1.05	.98
2-AYS ENG	12.00	1.05	.08
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	13.00	1.10	.22
ACC DRIVE G/B	42.00	1.25	1.40
APU	50.70	1.80	.69
APU STRT SYS	66.74	1.25	.49
OIL COOLING SYS	9.00	1.25	.15

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	0.0	0.0	21.8	52.7	APU	10.8 LB
HYD CHECKOUT	.250	0.	130.0	0.0	0.0	17.3	41.8	APU	9.8 LB
MAIN ENG1 START	.008	0.	130.0	0.0	0.0	24.0	58.0	APU	.4 LB
MAIN ENG2 START	.008	0.	130.0	0.0	0.0	24.0	58.0	APU	.4 LB
STANDBY	.083	0.	130.0	35.0	0.0	0.0	0.0	ME	2.9 LB
CRUISE	3.000	4000.	95.0	33.0	0.0	0.0	0.0	ME	54.4 LB

TOTAL SPS INST. WT. 465.29 LB. SPS INST. WT. PENALTY 1209.77 LB. SPS EXPENDABLE WT. PENALTY 165.37 LB.
TOTAL SPS INST. VOL. 5.19 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	323.75 LB	52.89	-1	-16.34	.10	-1.634
SYSTEM VOLUME	4.57 CU FT	.62	-1	-13.57	.05	-.678
TOGW PENALTY	1184.32 LB	190.80	-1	-16.11	.40	-6.444
RELIABILITY-MTBF	491.00 HRS	-34.00	+1	-6.92	.10	-.69
MAINTAINABILITY-MMH/FH	.080	.005	-1	-6.25	.05	-.312
AVAILABILITY	99.42	-.10	+1	-.10	.05	-.005
SYSTEM VULNERABILITY	100.00	8.00	-1	-8.00	.02	-.160
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	9.00	-1	-9.00	.05	-.450
LIFE CYCLE COST	100.00	23.92	-1	-23.92	.13	-3.110

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -13.686

TABLE LXIII - Continued

SYSTEM 1.2.0.1, II, WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	19.50	1.05	.49
PUMP FLT CTL	13.00	1.05	.36
PUMP APU	8.00	1.05	.04
MOTOR ADG	6.20	1.05	.03
SYS COMPONENTS-H	4.00	1.10	.02
2-40 KVA GENS	66.00	1.05	.42
SYS COMPONENTS-E	47.00	1.10	.56
2-ATS ENG	12.00	1.05	.08
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	11.00	1.10	.16
ACC DRIVE 8/8	42.00	1.25	1.40
APU	46.00	1.80	.53
APU STRT SYS	60.72	1.25	.44
OIL COOLING SYS	17.00	1.25	.24

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	44.7	0.0	0.0	44.7	APU	9.6 LB
HYD CHECKOUT	.250	0.	130.0	19.1	0.0	0.0	19.1	APU	7.2 LB
MAIN ENG1 START	.008	0.	130.0	26.6	0.0	10.8	52.7	APU	.3 LB
AMIN ENG2 START	.008	0.	130.0	26.6	0.0	10.8	52.7	APU	.3 LB
STANDBY	.083	0.	130.0	35.0	0.0	0.0	0.0	ME	2.9 LB
CRUISE	3.000	4000.	95.0	33.0	0.0	0.0	0.0	ME	54.4 LB

TOTAL SPS INST. WT. 457.31 LB. SPS INST. WT. PENALTY 1189.01 LB. SPS EXPENDABLE WT. PENALTY 157.34 LB.
TOTAL SPS INST. VOL. 5.03 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	323.75 LB	48.17	-1	-14.88	.10	-1.488
SYSTEM VOLUME	4.57 CU FT	.46	-1	-10.07	.05	-.503
TOGW PENALTY	1184.33 LB	162.02	-1	-13.68	.40	-5.472
RELIABILITY-MTBF	491.00 HRS	-46.00	+1	-9.37	.10	-.94
MAINTAINABILITY-MMH/FH	.080	.017	-1	-21.25	.05	-1.062
AVAILABILITY	99.42	-.21	+1	-.21	.05	-.011
SYSTEM VULNERABILITY	100.00	18.00	-1	-18.00	.02	-.360
AIRCRAFT COMPLEXITY	100.00	10.00	-1	-10.00	.05	-.500
SPS COMPLEXITY	100.00	18.00	-1	-18.00	.05	-.900
LIFE CYCLE COST	100.00	10.26	-1	-10.26	.13	-1.334

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -12.567

TABLE LXIII - Continued

SYSTEM 1.4.1.0, II, WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.70	1.05	.48
PUMP FLT CTL	13.00	1.05	.36
2-40 KVA GENS	66.00	1.05	.42
SYS COMPONENTS-E	47.00	1.10	.56
COMPRESSOR ADG	19.40	1.05	.22
2-ATS ENG	12.00	1.05	.08
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	10.00	1.10	.13
ACC DRIVE G/B	46.00	1.25	1.40
APU	47.40	1.80	.43
APU STRT SYS	51.54	1.25	.37
SHAFT-APU TO ADG	3.00	1.00	.05
OIL COOLING SYS	8.00	1.25	.13

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	31.4	0.0	0.0	31.4	APU	7.9 LB
HYD CHECKOUT	.250	0.	130.0	24.8	0.0	0.0	24.8	APU	7.3 LB
MAIN ENG1 START	.008	0.	130.0	44.9	0.0	0.0	44.9	APU	.3 LB
MAIN ENG2 START	.008	0.	130.0	44.9	0.0	0.0	44.9	APU	.3 LB
STANDBY	.083	0.	130.0	35.0	0.0	0.0	0.0	ME	2.9 LB
CRUISE	3.000	4000.	95.0	33.0	0.0	0.0	0.0	ME	54.4 LB

TOTAL SPS INST. WT. 441.28 LB. SPS INST. WT. PENALTY 1147.34 LB. SPS EXPENDABLE WT. PENALTY 153.69 LB.
TOTAL SPS INST. VOL. 4.89 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	323.75 LB	34.99	-1	-10.81	.10	-1.081
SYSTEM VOLUME	4.57 CU FT	.32	-1	-7.00	.05	-.350
TOG- PENALTY	1184.33 LB	116.70	-1	-9.85	.40	-3.941
RELIABILITY-MTBF	491.00 HRS	-26.00	+1	-5.30	.10	-.53
MAINTAINABILITY-MMH/FH	.080	.001	-1	-1.25	.05	-.062
AVAILABILITY	99.42	-.04	+1	-.04	.05	-.002
SYSTEM VULNERABILITY	100.00	7.00	-1	-7.00	.02	-.140
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	8.00	-1	-8.00	.05	-.400
LIFE CYCLE COST	100.00	18.74	-1	-18.74	.13	-2.436

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -9.142

TABLE LXIII - Continued

SYSTEM 2.4.1.0. II. WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.70	1.05	.48
PUMP FLT CTL	13.00	1.05	.36
2-40 KVA GENS	66.00	1.05	.42
SYS COMPONENTS-E	47.00	1.10	.56
COMPRESSOR ADG	19.60	1.05	.22
2-ATS ENG	12.00	1.05	.08
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS	10.00	1.10	.13
ACC DRIVE G/B	49.00	1.25	1.50
APU	47.40	1.80	.43
APU STRT SYS	51.54	1.25	.37
OIL COOLING SYS	8.00	1.25	.13

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	29.2	0.0	0.0	29.2	APU	7.7 LB
HYD CHECKOUT	.250	0.	130.0	24.8	0.0	0.0	24.8	APU	7.3 LB
MAIN ENG1 START	.008	0.	130.0	44.9	0.0	0.0	44.9	APU	.3 LB
MAIN ENG2 START	.008	0.	130.0	44.9	0.0	0.0	44.9	APU	.3 LB
STANDBY	.083	0.	130.0	35.0	0.0	0.0	0.0	ME	2.9 LB
CRUISE	3.000	4000.	95.0	33.0	0.0	0.0	0.0	ME	54.4 LB

TOTAL SPS INST. WT. 442.03 LB. SPS INST. WT. PENALTY 1149.29 LB. SPS EXPENDABLE WT. PENALTY 153.23 LB.
TOTAL SPS INST. VOL. 4.94 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	323.75 LB	34.99	-1	-10.81	.10	-1.081
SYSTEM VOLUME	4.57 CU FT	.37	-1	-8.10	.05	-.405
TOGW PENALTY	1194.33 LB	118.19	-1	-9.98	.40	-3.992
RELIABILITY-MTRF	491.00 HRS	-25.00	+1	-5.09	.10	-.51
MAINTAINABILITY-MMH/FH	.080	0.000	-1	-0.00	.05	0.000
AVAILABILITY	99.42	-.06	+1	-.06	.05	-.003
SYSTEM VULNERABILITY	100.00	3.00	-1	-3.00	.02	-.060
AIRCRAFT COMPLEXITY	100.00	2.00	-1	-2.00	.05	-.100
SPS COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
LIFE CYCLE COST	100.00	17.36	-1	-17.36	.13	-2.257

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -8.606

TABLE LXIII - Continued

SYSTEM 1.4.0.1, II, WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.70	1.05	.48
PUMP FLT CTL	13.00	1.05	.36
2-40 KVA GENS	66.00	1.05	.42
SYS COMPONENTS-E	47.00	1.10	.56
2-ATS ENG	12.00	1.05	.08
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	10.00	1.10	.13
ACC DRIVE G/B	41.00	1.25	1.30
APU	40.30	1.80	.46
APU STRT SYS	48.25	1.25	.34
SHAFT-APU TO ADG	3.00	1.00	.05
OIL COOLING SYS	8.00	1.25	.13

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	31.4	0.0	0.0	31.4	APU	7.2 LB
HYD CHECKOUT	.250	0.	130.0	24.8	0.0	0.0	24.8	APU	6.6 LB
MAIN ENG1 START	.008	0.	130.0	15.9	0.0	10.8	42.0	APU	.3 LB
MAIN ENG2 START	.008	0.	130.0	15.9	0.0	10.8	42.0	APU	.3 LB
STANDBY	.083	0.	130.0	35.0	0.0	0.0	0.0	ME	2.9 LB
CRUISE	3.000	4000.	95.0	33.0	0.0	0.0	0.0	ME	54.4 LB

TOTAL SPS INST. WT. 397.56 LB. SPS INST. WT. PENALTY 1033.66 LB. SPS EXPENDABLE WT. PENALTY 150.67 LB.
TOTAL SPS INST. VOL. 4.57 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	323.75 LB	-.00	-1	.00	.10	.000
SYSTEM VOLUME	4.57 CU FT	-.00	-1	.00	.05	.000
TOGW PENALTY	1184.33 LB	-.00	-1	.00	.40	.000
RELIABILITY-MTBF	491.00 HRS	0.00	+1	0.00	.10	0.00
MAINTAINABILITY-MMH/FH	.080	0.000	-1	-0.00	.05	0.000
AVAILABILITY	99.42	0.00	+1	0.00	.05	0.000
SYSTEM VULNERABILITY	100.00	0.00	-1	-0.00	.02	0.000
AIRCRAFT COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
SPS COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
LIFE CYCLE COST	100.00	0.00	-1	-0.00	.13	0.000

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT .000

TABLE LXIII - Concluded

SYSTEM 2.4.0.1, II, WITHOUT ECS

SYSTEM COMPONENTS	WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.70	1.05	.48
PUMP FLT CTL	13.00	1.05	.36
2-40 KVA GENS	66.00	1.05	.42
SYS COMPONENTS-E	47.00	1.10	.56
2-ATS ENG	12.00	1.05	.08
HEATER	13.50	1.35	.19
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	10.00	1.10	.13
ACC DRIVE G/B	44.00	1.25	1.40
APU	40.20	1.80	.46
APU STRT SYS	48.25	1.25	.34
OIL COOLING SYS	8.00	1.25	.13

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	29.5	0.0	0.0	29.5	APU	7.0 LB
HYD CHECKOUT	.250	0.	130.0	24.8	0.0	0.0	24.8	APU	6.6 LB
MAIN ENG1 START	.008	0.	130.0	15.9	0.0	10.8	42.0	APU	.3 LB
MAIN ENG2 START	.008	0.	130.0	15.9	0.0	10.8	42.0	APU	.3 LB
STANDBY	.083	0.	130.0	35.0	0.0	0.0	0.0	ME	2.9 LB
CRUISE	3.000	4000.	95.0	33.0	0.0	0.0	0.0	ME	54.4 LB

TOTAL SPS INST. WT. 398.13 LB.

TOTAL SPS INST. VOL. 4.62 CU. FT.

SPS INST. WT. PENALTY 1035.14 LB.

SPS EXPENDABLE WT. PENALTY 150.28 LB.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	323.75 LB	-.10	-1	.03	.10	.003
SYSTEM VOLUME	4.57 CU FT	.05	-1	-1.09	.05	-.055
TOGW PENALTY	1184.33 LB	1.10	-1	-.09	.40	-.037
RELIABILITY-MTBF	491.00 HRS	2.00	+1	.41	.10	.04
MAINTAINABILITY-MMH/FH	.080	-.001	-1	1.25	.05	.062
AVAILABILITY	99.42	-.01	+1	-.01	.05	-.001
SYSTEM VULNERABILITY	100.00	-4.00	-1	4.00	.02	.080
AIRCRAFT COMPLEXITY	100.00	-2.00	-1	2.00	.05	.100
SPS COMPLEXITY	100.00	-5.00	-1	5.00	.05	.250
LIFE CYCLE COST	100.00	.60	-1	-.60	.13	-.078

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT .366

TABLE LXIV. SYSTEMS WITH ECS

SYSTEM 1.4.1.0, II, WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.70	1.05	.48
PUMP FLT CTL	13.00	1.05	.36
2-40 KVA GENS	66.00	1.05	.42
SYS COMPONENTS-E	47.00	1.10	.56
COMPRESSOR ADG	20.80	1.05	.25
2-ATS ENG	12.00	1.05	.08
ECS	24.00	1.35	.90
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-F	10.00	1.10	.13
ACC DRIVE G/B	46.00	1.25	1.40
APU	58.20	1.80	.57
APU STRT SYS	80.33	1.25	.61
SHAFT-APU TO ADG	3.00	1.00	.05
OIL COOLING SYS	9.00	1.25	.15

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	70.3	0.0	0.0	70.3	APU	13.2 LB
HYD CHECKOUT	.250	0.	130.0	63.7	0.0	0.0	63.7	APU	12.5 LB
MAIN ENG1 START	.008	0.	130.0	44.9	0.0	0.0	44.9	APU	.4 LB
MAIN ENG2 START	.008	0.	130.0	44.9	0.0	0.0	44.9	APU	.4 LB
STANDBY	.083	0.	130.0	35.0	0.0	14.3	0.0	ME	4.6 LB
CRUISE	3.000	4000.	95.0	33.0	0.0	14.3	0.0	ME	114.5 LB

TOTAL SPS INST. WT. 513.40 LB. SPS INST. WT. PENALTY 1334.83 LB. SPS EXPENDABLE WT. PENALTY 305.57 LB.
TOTAL SPS INST. VOL. 6.03 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	379.79 LB	31.24	-1	-8.23	.10	-.823
SYSTEM VOLUME	5.79 CU FT	.24	-1	-4.15	.05	-.207
TOGW PENALTY	1548.70 LB	91.70	-1	-5.92	.40	-2.368
RELIABILITY-MTBF	433.00 HRS	-21.00	+1	-4.85	.10	-.48
MAINTAINABILITY-MMH/FH	.085	.001	-1	-1.18	.05	-.059
AVAILABILITY	99.33	-.05	+1	-.05	.05	-.003
SYSTEM VULNERABILITY	100.00	7.00	-1	-7.00	.02	-.140
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	9.00	-1	-9.00	.05	-.450
LIFE CYCLE COST	100.00	17.75	-1	-17.75	.13	-2.307
SPS TOTAL WEIGHTED PERCENT IMPROVEMENT						-7.042

TABLE LXIV - Continued

SYSTEM 2.4.1.0, II, WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.70	1.05	.48
PUMP FLT CTL	13.00	1.05	.36
2-40 KVA GENS	66.00	1.05	.42
SYS COMPONENTS-E	47.00	1.10	.56
COMPRESSOR ADG	20.80	1.05	.25
2-ATS ENG	12.00	1.05	.08
ECS	24.00	1.35	.90
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	10.00	1.10	.13
ACC DRIVE G/B	46.00	1.25	1.40
APU	58.20	1.80	.57
APU STRT SYS	80.33	1.25	.61
OIL COOLING SYS	9.00	1.25	.15

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	70.3	0.0	0.0	70.3	APU	13.2 LB
HYD CHECKOUT	.250	0.	130.0	63.7	0.0	0.0	63.7	APU	12.5 LB
MAIN ENG1 START	.008	0.	130.0	44.9	0.0	0.0	44.9	APU	.4 LB
MAIN ENG2 START	.008	0.	130.0	44.9	0.0	0.0	44.9	APU	.4 LB
STANDBY	.083	0.	130.0	35.0	0.0	14.3	0.0	ME	4.6 LB
CRUISE	3.000	4000.	95.0	33.0	0.0	14.3	0.0	ME	114.5 LB

TOTAL SPS INST. WT. 510.40 LB. SPS INST. WT. PENALTY 1327.03 LB. SPS EXPENDABLE WT. PENALTY 305.57 LB.
TOTAL SPS INST. VOL. 5.98 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	379.79 LB	28.24	-1	-7.44	.10	-.744
SYSTEM VOLUME	5.79 CU FT	.19	-1	-3.28	.05	-.164
TOGW PENALTY	1548.70 LB	83.90	-1	-5.42	.40	-2.167
RELIABILITY-MTBF	433.00 HRS	-19.00	+1	-4.39	.10	-.44
MAINTAINABILITY-MMH/FH	.085	0.000	-1	-0.00	.05	0.000
AVAILABILITY	99.33	-.07	+1	-.07	.05	-.004
SYSTEM VULNERABILITY	100.00	3.00	-1	-3.00	.02	-.060
AIRCRAFT COMPLEXITY	100.00	2.00	-1	-2.00	.05	-.100
SPS COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
LIFE CYCLE COST	100.00	16.44	-1	-16.44	.13	-2.137

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -6.014

TABLE LXIV - Continued

SYSTEM [illegible].0. II. WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	21.00	1.05	.69
PUMP FLT CTL	13.00	1.05	.36
2-MOTOR ENG STRT	25.00	1.05	.12
SYS COMPONENTS-H	9.90	1.10	.04
2-40 KVA GENS	66.00	1.05	.42
ECS	24.0	1.35	.90
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-E	47.00	1.10	.56
ACC DRIVE G/B	41.00	1.25	1.30
APU	59.40	1.80	.76
APU STRT SYS	76.20	1.25	.58
SHAFT-APU TO ADG	3.00	1.00	.05
OIL COOLING SYS	9.00	1.25	.15

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	32.8	0.0	14.3	67.3	APU	13.2 LB
HYD CHECKOUT	.250	0.	130.0	25.7	0.0	14.3	60.2	APU	12.5 LB
MAIN ENG1 START	.008	0.	130.0	42.0	0.0	0.0	42.0	APU	.4 LB
MAIN ENG2 START	.008	0.	130.0	42.0	0.0	0.0	42.0	APU	.4 LB
STANDBY	.083	0.	130.0	35.0	0.0	14.3	0.0	ME	4.6 LB
CRUISE	3.000	4000.	95.0	33.0	0.0	14.3	0.0	ME	114.5 LB

TOTAL SPS INST. WT. 501.41 LB. SPS INST. WT. PENALTY 1303.67 LB. SPS EXPENDABLE WT. PENALTY 305.70 LB.

TOTAL SPS INST. VOL. 5.00 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	379.79 LB	20.71	-1	-5.45	.10	-.545
SYSTEM VOLUME	5.79 CU FT	.21	-1	-3.63	.05	-.181
TOGW PENALTY	1548.70 LB	60.67	-1	-3.92	.40	-1.567
RELIABILITY-MTBF	433.00 HRS	33.00	+1	7.62	.10	.76
MAINTAINABILITY-MMH/FH	.085	.009	-1	-10.59	.05	-.529
AVAILABILITY	99.33	-.07	+1	-.07	.05	-.004
SYSTEM VULNERABILITY	100.00	10.00	-1	-10.00	.02	-.200
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	9.00	-1	-9.00	.05	-.450
LIFE CYCLE COST	100.00	1.68	-1	-1.68	.13	-.218

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -3.133

TABLE LXIV - Continued

SYSTEM 2.4.2.0, II, WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	21.00	1.05	.69
PUMP FLT CTL	13.00	1.05	.36
2-MOTOR ENG STRT	25.00	1.05	.12
ECS	24.30	1.35	.90
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-H	9.90	1.10	.04
2-40 KVA GENS	66.00	1.05	.42
SYS COMPONENTS-E	47.00	1.10	.56
ACC DRIVE G/B	41.00	1.25	1.30
APU	57.70	1.80	.72
APU STRT SYS	74.70	1.25	.56
OIL COOLING SYS	9.00	1.25	.15

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	30.6	0.0	14.3	65.[illegible]	APU	12.9 LB
HYD CHECKOUT	.250	0.	130.0	25.[illegible]	0.0	[illegible]	[illegible]	APU	12.4 LB
MAIN ENG1 START	.008	0.	130.0	42.0	0.0	[illegible]	[illegible]	APU	.4 LB
MAIN ENG2 START	.008	0.	130.0	42.0	0.0	[illegible]	[illegible]	APU	.4 LB
STANDBY	.083	0.	130.0	35.0	0.0	14.[illegible]	[illegible]	MF	4.6 LB
CRUISE	3.000	4000.	95.0	33.0	0.0	14.[illegible]	[illegible]	MF	114.5 LB

TOTAL SPS INST. WT. 493.47 LB. SPS INST. WT. PENALTY 1283.03 LB. SPS EXPENDABLE WT. PENALTY 304.68 LB.

TOTAL SPS INST. VOL. 5.89 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	379.79 LB	[illegible]	-1	-3.82	.10	-.382
SYSTEM VOLUME	5.79 CU FT	.10	-1	-1.73	.05	-.086
TOGW PENALTY	1548.70 LB	39.01	-1	-2.52	.40	-1.008
RELIABILITY-MTBF	433.00 HRS	35.00	+1	8.08	.10	.81
MAINTAINABILITY-MMH/FH	.085	.008	-1	-9.41	.05	-.471
AVAILABILITY	99.33	-.09	+1	-.09	.05	-.005
SYSTEM VULNERABILITY	100.00	6.00	-1	-6.00	.02	-.120
AIRCRAFT COMPLEXITY	100.00	2.00	-1	-2.00	.05	-.100
SPS COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
LIFE CYCLE COST	100.00	2.25	-1	-2.25	.13	-.292

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -1.855

TABLE LXIV - Continued

SYSTEM 1.4.0.1, II, WITH ECS

SYSTEM COMPONENTS	WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.70	1.05	.48
PUMP FLT CTL	13.00	1.05	.36
2-40 KVA GENS	66.00	1.05	.42
SYS COMPONENTS-E	47.00	1.10	.56
2-ATS ENG	12.00	1.05	.08
ECS	24.00	1.35	.90
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	10.00	1.10	.13
ACC DRIVE G/B	41.00	1.25	1.30
APU	57.50	1.80	.72
APU STRT SYS	75.50	1.25	.57
SHAFT-APU TO ADG	3.00	1.00	.05
OIL COOLING SYS	9.00	1.25	.15

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	31.4	0.0	14.3	65.9	APU	13.2 LB
HYD CHECKOUT	.250	0.	130.0	24.8	0.0	14.3	59.3	APU	12.5 LB
MAIN ENG1 START	.008	0.	130.0	15.9	0.0	10.7	41.8	APU	.4 LB
MAIN ENG2 START	.008	0.	130.0	15.9	0.0	10.7	41.8	APU	.4 LB
STANDBY	.083	0.	130.0	35.0	0.0	14.3	0.0	ME	4.6 LB
CRUISE	3.000	4000.	95.3	33.0	0.0	14.3	0.0	ME	114.5 LB

TOTAL SPS INST. WT. 478.12 LB. SPS INST. WT. PENALTY 1243.12 LB. SPS EXPENDABLE WT. PENALTY 305.58 LB.
TOTAL SPS INST. VOL. 5.79 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	379.79 LB	-.00	-1	.00	.10	.000
SYSTEM VOLUME	5.79 CU FT	-.00	-1	.00	.05	.000
TOGW PENALTY	1548.70 LB	-.00	-1	.00	.40	.000
RELIABILITY-MTBF	433.00 HRS	0.00	+1	0.00	.10	0.00
MAINTAINABILITY-MMH/FH	.085	0.000	-1	-0.00	.05	0.000
AVAILABILITY	99.33	0.00	+1	0.00	.05	0.000
SYSTEM VULNERABILITY	100.00	0.00	-1	-0.00	.02	0.000
AIRCRAFT COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
SPS COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
LIFE CYCLE COST	100.00	0.00	-1	-0.00	.13	0.000

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT .000

TABLE LXIV - Concluded

SYSTEM 2.4.0.1, II, WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.70	1.05	.48
PUMP FLT CTL	13.00	1.05	.36
2-40 KVA GENS	66.00	1.05	.42
SYS COMPONENTS-E	47.00	1.10	.56
2-ATS ENG	12.00	1.05	.08
ECS	24.00	1.35	.90
VENT FAN	6.00	1.25	.07
SYS COMPONENTS-P	10.00	1.10	.13
ACC DRIVE G/B	41.00	1.25	1.30
APU	55.90	1.80	.71
APU STRT SYS	73.48	1.25	.55
OIL COOLING SYS	9.00	1.25	.15

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	29.5	0.0	14.3	64.0	APU	12.7 LB
HYD CHECKOUT	.250	0.	130.0	24.8	0.0	14.3	59.3	APU	12.2 LB
MAIN ENG1 START	.008	0.	130.0	15.9	0.0	10.7	41.8	APU	.3 LB
MAIN ENG2 START	.008	0.	130.0	15.9	0.0	10.7	41.8	APU	.3 LB
STANDBY	.083	0.	130.0	35.0	0.0	14.3	0.0	ME	4.6 LB
CRUISE	3.000	4000.	95.0	33.0	0.0	14.3	0.0	ME	114.5 LB

TOTAL SPS INST. WT. 469.06 LB. SPS INST. WT. PENALTY 1219.57 LB. SPS EXPENDABLE WT. PENALTY 303.87 LB.
TOTAL SPS INST. VOL. 5.71 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	379.79 LB	-7.01	-1	1.85	.10	.185
SYSTEM VOLUME	5.79 CU FT	-.08	-1	1.38	.05	.069
TOGW PENALTY	1548.70 LB	-25.27	-1	1.63	.40	.653
RELIABILITY-MTBF	433.00 HRS	2.00	+1	.46	.10	.05
MAINTAINABILITY-MMH/FH	.085	-.001	-1	1.18	.05	.059
AVAILABILITY	99.33	-.02	+1	-.02	.05	-.001
SYSTEM VULNERABILITY	100.00	-4.00	-1	4.00	.02	.080
AIRCRAFT COMPLEXITY	100.00	-2.00	-1	2.00	.05	.100
SPS COMPLEXITY	100.00	-5.00	-1	5.00	.05	.250
LIFE CYCLE COST	100.00	.57	-1	-.57	.13	-.074

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT 1.366

TECHNOLOGY LEVEL III

TABLE LXV:

SYSTEM TITLE	WEIGHTED PERCENT SPS IMPROVEMENT
SYSTEM 1.2.0.1, III, WITHOUT ECS	-10.442
SYSTEM 1.1.0.1, III, WITHOUT ECS	-10.186
SYSTEM 1.4.1.0, III, WITHOUT ECS	-6.197
SYSTEM 2.4.1.0, III, WITHOUT ECS	-5.737
SYSTEM 1.4.0.1, III, WITHOUT ECS	.000
SYSTEM 2.4.0.1, III, WITHOUT ECS	.297

TABLE LXVI:

SYSTEM 1.4.1.0, III, WITH ECS	-5.389
SYSTEM 2.4.1.0, III, WITH ECS	-4.314
SYSTEM 1.4.2.0, III, WITH ECS	-3.923
SYSTEM 2.4.2.0, III, WITH ECS	-3.209
SYSTEM 1.4.0.1, III, WITH ECS	-.000
SYSTEM 2.4.0.1, III, WITH ECS	.[illegible]19

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TABLE LXV. SYSTEMS WITHOUT ECS

SYSTEM 1.2.0.1, III, WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	17.70	1.05	.48
PUMP FLT CTL	12.50	1.05	.35
PUMP APU	5.50	1.05	.03
MOTOR ADG	4.00	1.05	.02
SYS COMPONENTS-(	3.60	1.10	.02
2-40 KVA GENS	60.00	1.05	.38
SYS COMPONENTS-E	42.00	1.10	.49
2-ATS ENG	9.00	1.05	.06
HEATER	12.00	1.35	.19
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-P	8.00	1.10	.10
ACC DRIVE G/B	37.00	1.25	1.30
APU	39.00	1.50	.26
APU STRT SYS	26.61	1.25	.16
OIL COOLING SYS	14.00	1.25	.20

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	40.1	0.0	0.0	40.1	APU	7.0 LB
HYD CHECKOUT	.250	0.	130.0	17.3	0.0	0.0	17.3	APU	5.3 LB
MAIN ENG1 START	.008	0.	130.0	22.9	0.0	8.8	47.8	APU	.3 LB
MAIN ENG2 START	.008	0.	130.0	22.9	0.0	8.8	47.8	APU	.3 LB
STANDBY	.083	0.	130.0	33.0	0.0	0.0	0.0	ME	2.7 LB
CRUISE	3.000	4000.	95.0	31.0	0.0	0.0	0.0	ME	51.1 LB

TOTAL SPS INST. WT. 363.38 LB. SPS INST. WT. PENALTY 944.79 LB. SPS EXPENDABLE WT. PENALTY 140.02 LB.
TOTAL SPS INST. VOL. 4.11 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT ULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	267.34 LB	29.07	-1	-10.87	.10	-1.087
SYSTEM VOLUME	3.85 CU FT	.26	-1	-6.75	.05	-.338
TOGW PENALTY	988.22 LB	96.59	-1	-9.77	.40	-3.910
RELIABILITY-MTBF	586.00 HRS	-61.00	+1	-10.41	.10	-1.04
MAINTAINABILITY-MMH/FH	.078	.017	-1	-21.79	.05	-1.090
AVAILABILITY	99.51	-.17	+1	-.17	.05	-.009
SYSTEM VULNERABILITY	100.00	10.00	-1	-18.00	.02	-.360
AIRCRAFT COMPLEXITY	100.00	10.00	-1	-10.00	.05	-.500
SPS COMPLEXITY	100.00	18.00	-1	-18.00	.05	-.900
LIFE CYCLE COST	100.00	9.29	-1	-9.29	.13	-1.208
				SPS TOTAL WEIGHTED PERCENT IMPROVEMENT		-10.442

TABLE LXV - Continued

SYSTEM 1.1.0.1. III. WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.20	1.05	.47
PUMP FLT CTL	12.50	1.05	.35
2-40 KVA GENS	60.00	1.05	.38
SYS COMPONENTS-E	42.00	1.10	.49
ATM ADG	16.30	1.05	.05
2-ATS ENG	9.00	1.05	.06
HEATER	12.00	1.35	.19
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-P	9.00	1.10	.11
ACC DRIVE G/B	37.00	1.25	1.30
APU	43.90	1.80	.27
APU STRT SYS	26.58	1.25	.16
OIL COOLING SYS	8.00	1.25	.12

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	0.0	0.0	16.6	46.9	APU	7.5 LB
HYD CHECKOUT	.250	0.	130.0	0.0	0.0	14.3	40.4	APU	6.9 LB
MAIN ENG1 START	.008	0.	130.0	0.0	0.0	16.9	47.7	APU	.3 LB
MAIN ENG2 START	.008	0.	130.0	0.0	0.0	16.9	47.7	APU	.3 LB
STANDBY	.083	0.	130.0	33.0	0.0	0.0	0.0	ME	2.7 LB
CRUISE	3.000	4000.	95.0	31.0	0.0	0.0	0.0	ME	51.1 LB

TOTAL SPS INST. WT. 366.37 LB. SPS INST. WT. PENALTY 952.43 LB. SPS EXPENDABLE WT. PENALTY 144.44 LB.
TOTAL SPS INST. VOL. 4.02 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	267.34 LB	29.64	-1	-11.09	.10	-1.109
SYSTEM VOLUME	3.85 CU FT	.17	-1	-4.42	.05	-.221
TOGW PENALTY	988.22 LB	108.65	-1	-10.99	.40	-4.398
RELIABILITY-MTBF	586.00 HRS	-34.00	+1	-5.80	.10	-.58
MAINTAINABILITY-MMH/FH	.078	.002	-1	-2.56	.05	-.128
AVAILABILITY	99.51	-.05	+1	-.05	.05	-.003
SYSTEM VULNERABILITY	100.00	8.00	-1	-8.00	.02	-.160
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	9.00	-1	-9.00	.05	-.450
LIFE CYCLE COST	100.00	22.60	-1	-22.60	.13	-2.938

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -10.186

TABLE LXV - Continued

SYSTEM 1.4.1.0. III. WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.20	1.05	.47
PUMP FLT CTL	12.50	1.05	.35
2-40 KVA GENS	60.00	1.05	.38
SYS COMPONENTS-E	42.00	1.10	.49
COMPRESSOR ADG	16.50	1.05	.18
2-ATS ENG	9.00	1.05	.06
HEATER	12.00	1.35	.19
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-P	7.00	1.10	.09
ACC DRIVE G/B	40.00	1.25	1.30
APU	30.30	1.80	.22
APU STRT SYS	24.13	1.25	.13
SHAFT-APU TO ADG	2.50	1.00	.05
OIL COOLING SYS	7.00	1.25	.11

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	28.8	0.0	0.0	28.8	APU	5.7 LB
HYD CHECKOUT	.250	0.	130.0	22.9	0.0	0.0	22.9	APU	5.2 LB
MAIN ENG1 START	.008	0.	130.0	40.4	0.0	0.0	40.4	APU	.2 LB
MAIN ENG2 START	.008	0.	130.0	40.4	0.0	0.0	40.4	APU	.2 LB
STANDBY	.083	0.	130.0	33.0	0.0	0.0	0.0	ME	2.7 LB
CRUISE	3.000	4000.	95.0	31.0	0.0	0.0	0.0	ME	51.1 LB

TOTAL SPS INST. WT. 341.79 LB. SPS INST. WT. PENALTY 888.65 LB. SPS EXPENDABLE WT. PENALTY 136.91 LB.
TOTAL SPS INST. VOL. 4.09 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	267.34 LB	16.29	-1	-6.09	.10	-.609
SYSTEM VOLUME	3.85 CU FT	.24	-1	-6.23	.05	-.312
TOGW PENALTY	988.22 LB	37.34	-1	-3.78	.40	-1.511
RELIABILITY-MTBF	586.00 HRS	-35.00	+1	-5.97	.10	-.60
MAINTAINABILITY-MMH/FH	.078	.001	-1	-1.28	.05	-.064
AVAILABILITY	99.51	-.05	+1	-.05	.05	-.003
SYSTEM VULNERABILITY	100.00	7.00	-1	-7.00	.02	-.140
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	8.00	-1	-8.00	.05	-.400
LIFE CYCLE COST	100.00	18.16	-1	-18.16	.13	-2.361

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -6.197

TABLE LXV - Continued

SYSTEM 2.4.1.0, III, WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.20	1.05	.47
PUMP FLT CTL	12.50	1.05	.35
2-40 KVA GENS	60.00	1.05	.38
SYS COMPONENTS-E	42.00	1.10	.49
COMPRESSOR ADG	16.50	1.05	.18
2-ATS ENG	9.00	1.05	.06
HEATER	12.00	1.35	.19
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-P	7.00	1.10	.09
ACC DRIVE G/B	43.00	1.25	1.40
APU	30.30	1.80	.22
APU STRT SYS	24.13	1.25	.13
OIL COOLING SYS	7.00	1.25	.11

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	28.8	0.0	0.0	28.8	APU	5.7 LB
HYD CHECKOUT	.250	0.	130.0	22.9	0.0	0.0	22.9	APU	5.2 LB
MAIN ENG1 START	.008	0.	130.0	40.4	0.0	0.0	40.4	APU	.2 LB
MAIN ENG2 START	.008	0.	130.0	40.4	0.0	0.0	40.4	APU	.2 LB
STANDBY	.083	0.	130.0	33.0	0.0	0.0	0.0	ME	2.7 LB
CRUISE	3.000	4000.	95.0	31.0	0.0	0.0	0.0	ME	51.1 LB

TOTAL SPS INST. WT. 343.04 LB.   SPS INST. WT. PENALTY 891.90 LB.   SPS EXPENDABLE WT. PENALTY 136.91 LB.
TOTAL SPS INST. VOL. 4.14 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	267.34 LB	16.79	-1	-6.28	.10	-.628
SYSTEM VOLUME	3.85 CU FT	.29	-1	-7.53	.05	-.377
TOGW PENALTY	988.22 LB	40.59	-1	-4.11	.40	-1.643
RELIABILITY-MTBF	586.00 HRS	-32.00	-1	-5.46	.10	-.55
MAINTAINABILITY-MMH/FH	.078	0.000	-1	-0.00	.05	0.000
AVAILABILITY	99.51	-.04	-1	-.04	.05	-.002
SYSTEM VULNERABILITY	100.00	3.00	-1	-3.00	.02	-.060
AIRCRAFT COMPLEXITY	100.00	2.00	-1	-2.00	.05	-.100
SPS COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
LIFE CYCLE COST	100.00	16.78	-1	-16.78	.13	-? 81

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -5.737

TABLE LXV - Continued

SYSTEM 1.4.0.1. III. WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.20	1.05	.47
PUMP FLT CTL	12.50	1.05	.35
2-40 KVA GENS	60.00	1.05	.38
SYS COMPONENTS-E	42.00	1.10	.49
2-ATS ENG	9.00	1.05	.06
HEATER	12.00	1.35	.19
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-P	7.00	1.10	.09
ACC DRIVE G/B	35.09	1.25	1.20
APU	36.00	1.80	.26
APU STRT SYS	23.64	1.25	.13
SHAFT-APU TO ADG	2.50	1.00	.05
OIL COOLING SYS	7.00	1.25	.11

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	28.8	0.0	0.0	28.8	APU	5.4 LB
HYD CHECKOUT	.250	0.	130.0	22.9	0.0	0.0	22.9	APU	4.9 LB
MAIN ENG1 START	.008	0.	130.0	14.0	0.0	8.8	38.9	APU	.2 LB
MAIN ENG2 START	.008	0.	130.0	14.0	0.0	8.8	38.9	APU	.2 LB
STANDBY	.083	0.	130.0	33.0	0.0	0.0	0.0	ME	2.7 LB
CRUISE	3.000	-030.	95.0	31.0	0.0	0.0	0.0	ME	51.1 LB

TOTAL SPS INST. WT. 327.86 LB.
TOTAL SPS INST. VOL. 3.85 CU. FT.

SPS INST. WT. PENALTY 852.44 LB.

SPS EXPENDABLE WT. PENALTY 135.78 LB.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	267.34 LB	-.00	-1	.00	.10	.000
SYSTEM VOLUME	3.85 CU FT	-.00	-1	.00	.05	.000
TOGW PENALTY	988.22 LB	-.00	-1	.00	.40	.000
RELIABILITY-MTBF	586.00 HRS	0.00	+1	0.00	.10	0.00
MAINTAINABILITY-MMH/FH	.078	0.000	-1	-0.00	.05	0.000
AVAILABILITY	99.51	0.00	+1	0.00	.05	0.000
SYSTEM VULNERABILITY	100.00	0.00	-1	-0.00	.02	0.000
AIRCRAFT COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
SPS COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
LIFE CYCLE COST	100.00	0.00	-1	-0.00	.13	0.000

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT .000

TABLE LXV - Concluded

SYSTEM 2.4.0.1. III. WITHOUT ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.20	1.05	.47
PUMP FLT CTL	12.50	1.05	.35
2-40 KVA GENS	60.00	1.05	.38
SYS COMPONENTS-E	42.00	1.10	.49
2-ATS ENG	9.00	1.05	.06
HEATER	12.00	1.35	.19
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-P	7.00	1.10	.09
ACC DRIVE G/B	38.00	1.25	1.30
APU	36.00	1.80	.26
APU STRT SYS	23.64	1.25	.13
OIL COOLING SYS	7.00	1.25	.11

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	28.8	0.0	0.0	28.8	APU	5.4 LB
HYD CHECKOUT	.250	0.	130.0	22.9	0.0	0.0	22.9	APU	4.9 LB
MAIN ENG1 START	.008	0.	130.0	14.0	0.0	8.8	38.9	APU	.2 LB
MAIN ENG2 START	.008	0.	130.0	14.0	0.0	8.8	38.9	APU	.2 LB
STANDBY	.083	0.	130.0	33.0	0.0	0.0	0.0	ME	2.7 LB
CRUISE	3.000	4000.	95.0	31.0	0.0	0.0	0.0	ME	51.1 LB

TOTAL SPS INST. WT. 329.11 LB. SPS INST. WT. PENALTY 855.69 LB. SPS EXPENDABLE WT. PENALTY 135.78 LB.
TOTAL SPS INST. VOL. 3.90 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	267.34 LB	.50	-1	-.19	.10	-.019
SYSTEM VOLUME	3.85 CU FT	.05	-1	-1.30	.05	-.065
TOGW PENALTY	988.22 LB	3.25	-1	-.33	.40	-.131
RELIABILITY-MTBF	586.00 HRS	4.00	+1	.68	.10	.07
MAINTAINABILITY-MMH/FH	.078	-.001	-1	1.28	.05	.064
AVAILABILITY	99.51	.01	+1	.01	.05	.001
SYSTEM VULNERABILITY	100.00	-4.00	-1	4.00	.02	.080
AIRCRAFT COMPLEXITY	100.00	-2.00	-1	2.00	.05	.100
SPS COMPLEXITY	100.00	-5.00	-1	5.00	.05	.250
LIFE CYCLE COST	100.00	.39	-1	-.39	.13	-.051

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT .297

TABLE LXVI. SYSTEMS WITH ECS

SYSTEM 1.4.1.0. III. WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.20	1.05	.47
PUMP FLT CTL	12.50	1.05	.35
2-40 KVA GENS	60.00	1.05	.38
SYS COMPONENTS-E	42.00	1.10	.49
COMPRESSOR ADG	16.70	1.05	.18
2-ATS ENG	9.00	1.05	.06
ECS	22.30	1.35	.75
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-P	7.00	1.10	.09
ACC DRIVE G/B	40.00	1.25	1.30
APU	37.90	1.90	.30
APU STRT SYS	30.97	1.25	.21
SHAFT-APU TO ADG	2.50	1.00	.05
OIL COOLING SYS	8.00	1.25	.12

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	59.9	0.0	0.0	59.9	APU	8.8 LB
HYD CHECKOUT	.250	0.	130.0	53.8	0.0	0.0	53.8	APU	8.3 LB
MAIN ENG1 START	.008	0.	130.0	39.9	0.0	0.0	39.9	APU	.2 LB
MAIN ENG2 START	.008	0.	130.0	39.9	0.0	0.0	39.9	APU	.2 LB
STANDBY	.083	0.	130.0	33.0	0.0	9.8	0.0	ME	3.9 LB
CRUISE	3.000	4000.	95.0	31.0	0.0	9.8	0.0	ME	92.3 LB

TOTAL SPS INST. WT. 379.38 LB. SPS INST. WT. PENALTY 986.39 LB. SPS EXPENDABLE WT. PENALTY 239.02 LB.

TOTAL SPS INST. VOL. 4.82 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	294.65 LB	14.92	-1	-5.06	.10	-.506
SYSTEM VOLUME	4.56 CU FT	.26	-1	-5.70	.05	-.285
TOGW PENALTY	1197.43 LB	27.98	-1	-2.34	.40	-.935
RELIABILITY-MTBF	524.00 HRS	-30.00	+1	-5.73	.10	-.57
MAINTAINABILITY-MMH/FH	.081	.001	-1	-1.23	.05	-.062
AVAILABILITY	99.44	-.06	[illegible]	-.06	.05	-.003
SYSTEM VULNERABILITY	100.00	7.00	-1	-7.00	.02	-.140
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	9.00	-1	-9.00	.05	-.450
LIFE CYCLE COST	100.00	17.20	-1	-17.20	.13	-2.236

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -5.389

TABLE LXVI - Continued

SYSTEM 2.4.1.0, III, WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.20	1.05	.47
PUMP FLT CTL	12.50	1.05	.35
2-40 KVA GENS	60.00	1.05	.38
SYS COMPONENTS-E	42.00	1.10	.49
COMPRESSOR ADG	16.70	1.05	.18
2-ATS ENG	9.00	1.05	.06
ECS	22.30	1.35	.75
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-P	7.00	1.11	.09
ACC DRIVE G/B	40.00	1.25	1.30
APU	37.90	1.83	.30
APU STRT SYS	30.97	1.25	.21
OIL COOLING SYS	8.00	1.25	.12

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	59.9	0.0	0.0	59.9	APU	8.8 LB
HYD CHECKOUT	.250	0.	130.0	53.8	0.0	0.0	53.8	APU	8.3 LB
MAIN ENG1 START	.008	0.	130.0	39.9	0.0	0.0	39.9	APU	.2 LB
MAIN ENG2 START	.008	0.	130.0	39.9	0.0	0.0	39.9	APU	.2 LB
STANDBY	.083	0.	130.0	33.0	0.0	9.8	0.0	ME	3.9 LB
CRUISE	3.000	4000.	95.0	31.0	0.0	9.8	0.0	ME	92.3 LB

TOTAL SPS INST. WT. 376.88 LB. SPS INST. WT. PENALTY 4[illegible].69 LB. SPS EXPENDABLE WT. PENALTY 239.02 LB.
TOTAL SPS INST. VOL. 4.77 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	294.65 LB	12.42	-1	-4.22	.10	-.422
SYSTEM VOLUME	4.56 CU FT	.21	-1	-4.61	.05	-.230
TOGW PENALTY	1197.43 LB	21.48	-1	-1.79	.40	-.718
RELIABILITY-MTBF	524.00 HRS	-27.00	+1	-5.15	.10	-.52
MAINTAINABILITY-MMH/FH	.081	0.000	-1	-0.00	.05	0.000
AVAILABILITY	99.46	-.05	+1	-.05	.05	-.003
SYSTEM VULNERABILITY	100.00	3.00	-1	-3.00	.02	-.060
AIRCRAFT COMPLEXITY	100.00	2.00	-1	-2.00	.05	-.100
SPS COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
LIFE CYCLE COST	100.00	15.90	-1	-15.90	.13	-2.067

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -4.314

TABLE LXVI - Continued

SYSTEM 1.4.2.0. III. WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	20.00	1.05	.68
PUMP FLT CTL	12.50	1.05	.35
2-MOTOR ENG STRT	23.00	1.05	.10
SYS COMPONENTS-H	9.00	1.10	.04
2-40 KVA GENS	60.00	1.05	.38
ECS	22.30	1.35	.75
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-E	42.00	1.10	.49
ACC DRIVE G/B	35.00	1.25	1.20
APU	47.20	1.80	.36
APU STRT SYS	30.28	1.25	.20
SHAFT-APU TO ADG	2.50	1.60	.05
OIL COOLING SYS	8.00	1.25	.12

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	30.1	0.0	9.8	57.8	APU	9.1 LB
HYD CHECKOUT	.250	0.	130.0	23.8	0.0	9.8	51.5	APU	8.6 LB
MAIN ENG1 START	.008	0.	130.0	40.2	0.0	0.0	40.2	APU	.3 LB
MAIN ENG2 START	.008	0.	130.0	40.2	0.0	0.0	40.2	APU	.3 LB
STANDBY	.083	0.	130.0	33.0	0.0	9.8	0.0	ME	3.9 LB
CRUISE	3.000	4000.	95.0	31.0	0.0	9.8	0.0	ME	92.3 LB

TOTAL SPS INST. WT. 394.40 LB. SPS INST. WT. PENALTY 1025.45 LB. SPS EXPENDABLE WT. PENALTY 240.33 LB.
TOTAL SPS INST. VOL. 4.79 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	294.65 LB	23.53	-1	-7.99	.10	-.799
SYSTEM VOLUME	4.56 CU FT	.23	-1	-5.04	.05	-.252
TOGW PENALTY	1197.43 LB	[illegible].35	-1	-5.71	.40	-2.283
RELIABILITY-MTBF	524.00 HRS	30.00	+1	5.73	.10	.57
MAINTAINABILITY-MMH/FH	.081	.008	-1	-9.88	.05	-.494
AVAILABILITY	99.46	-.08	+1	-.08	.05	-.004
SYSTEM VULNERABILITY	100.00	10.00	-1	-10.00	.02	-.200
AIRCRAFT COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
SPS COMPLEXITY	100.00	9.00	-1	-9.00	.05	-.450
LIFE CYCLE COST	100.00	-1.43	-1	1.43	.13	.186

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -3.923

TABLE LXVI - Continued

SYSTEM 2.4.2.0. III. WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	20.00	1.05	.48
PUMP FLT CTL	12.50	1.05	.35
2-MOTOR ENG STRT	23.00	1.05	.10
SYS COMPONENTS-H	9.00	1.10	.04
2-40 KVA GENS	60.00	1.05	.38
ECS	22.30	1.35	.75
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-E	42.00	1.10	.49
ACC DRIVE G/B	35.00	1.25	1.20
APU	47.20	1.80	.36
APU STRT SYS	30.28	1.25	.20
OIL COOLING SYS	8.00	1.25	.12

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	30.1	0.0	9.8	57.8	APU	9.[illegible] LB
HYD CHECKOUT	.250	0.	130.0	23.8	0.0	9.8	51.5	APU	8.6 LB
MAIN ENG1 START	.008	0.	130.0	40.2	0.0	0.0	40.2	APU	.3 LB
MAIN ENG2 START	.008	0.	130.0	40.2	0.0	0.0	40.2	APU	.3 LB
STANDBY	.093	0.	130.0	33.0	0.0	9.8	0.0	ME	3.9 LB
CRUISE	3.000	4000.	95.0	31.0	0.0	9.8	0.0	ME	92.3 LB

TOTAL SPS INST. WT. 391.90 LB. SPS INST. WT. PENALTY 1018.95 LB. SPS EXPENDABLE WT. PENALTY 240.33 LB.
TOTAL SPS INST. VOL. 4.74 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	294.65 LB	21.03	-1	-7.14	.10	-.714
SYSTEM VOLUME	4.56 CU FT	.18	-1	-3.95	.05	-.197
TOGW PENALTY	1197.43 LB	61.85	-1	-5.17	.40	-2.066
RELIABILITY-MTBF	524.00 HRS	32.00	+1	6.11	.10	.61
MAINTAINABILITY-MMH/FH	.081	.009	-1	-11.11	.05	-.556
AVAILABILITY	99.46	-.07	+1	-.07	.05	-.004
SYSTEM VULNERABILITY	100.00	6.00	-1	-6.00	.02	-.120
AIRCRAFT COMPLEXITY	100.00	2.00	-1	-2.00	.05	-.100
SPS COMPLEXITY	100.00	4.00	-1	-4.00	.05	-.200
LIFE CYCLE COST	100.00	-1.05	-1	1.05	.13	.137

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -3.209

TABLE LXVI - Continued

SYSTEM 1.4.0.1, III, WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.20	1.05	.47
PUMP FLT CTL	12.50	1.05	.35
2-40 KVA GENS	63.00	1.05	.38
SYS COMPONENTS-E	42.00	1.17	.49
2-ATS ENG	9.00	1.05	.06
ECS	22.30	1.35	.75
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-P	7.00	1.10	.09
ACC DRIVE G/B	35.00	1.25	1.20
APU	45.70	1.80	.33
APU STRT SYS	29.95	1.25	.20
SHAFT-APU TO ADG	2.50	1.00	.05
OIL COOLING SYS	8.00	1.25	.12

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU ESHP	SHP SOURCE	FUEL BURNED
FLFC CHECKOUT	.250	0.	130.0	29.1	0.0	9.8	54.8	APU	9.0 LB
HYL CHECKOUT	.250	0.	130.0	22.9	0.0	9.4	50.6	APU	8.5 LB
MAIN ENG1 START	.008	0.	130.0	14.0	0.0	9.4	38.9	APU	.3 LB
MAIN ENG2 START	.008	0.	130.0	14.0	0.0	8.8	38.9	APU	.3 LB
STANDBY	.083	0.	130.0	33.0	0.0	9.8	0.0	ME	3.9 LB
CRUISE	3.000	4000.	95.0	31.0	0.0	9.8	0.0	ME	92.3 LB

TOTAL SPS INST. WT. 368.34 LB. SPS INST. WT. PENALTY 957.74 LB. SPS EXPENDABLE WT. PENALTY 239.69 LB.
TOTAL SPS INST. VOL. 4.56 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	294.65 LB	-.00	-1	.00	.10	.000
SYSTEM VOLUME	4.56 CU FT	-.00	-1	.00	.05	.000
TOGW PENALTY	1197.43 LB	.00	-1	-.00	.40	-.000
RELIABILITY-MTBF	524.00 HRS	0.00	+1	0.00	.10	0.00
MAINTAINABILITY-MMH/FH	.081	0.000	-1	-0.00	.05	0.000
AVAILABILITY	99.44	0.00	+1	0.00	.05	0.000
SYSTEM VULNERABILITY	100.00	0.00	-1	-0.00	.02	0.000
AIRCRAFT COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
SPS COMPLEXITY	100.00	0.00	-1	-0.00	.05	0.000
LIFE CYCLE COST	100.00	0.00	-1	-0.00	.13	0.000

SPS TOTAL WEIGHTED PERCENT IMPROVEMENT -.000

TABLE LXVI - Concluded

SYSTEM 2.4.0.1. III. WITH ECS

SYSTEM COMPONENTS	COMPONENT DATA WT. LB.	INS. FAC.	VOL.
PUMP UTIL	15.20	1.05	.47
PUMP FLT CTL	12.50	1.05	.35
2-40 KVA GENS	60.00	1.05	.38
SYS COMPONENTS-E	42.00	1.10	.49
2-ATS ENG	9.00	1.05	.06
ECS	22.30	1.35	.75
VENT FAN	5.50	1.25	.07
SYS COMPONENTS-P	7.00	1.10	.09
ACC DRIVE G/B	35.00	1.25	1.20
APU	45.70	1.80	.33
APU STRT SYS	29.95	1.25	.20
OIL COOLING SYS	8.70	1.25	.12

MISSION SEGMENT	TIME HRS.	ALT FT.	TAMB DEGF	SHAFT POWER	ECS SHP	BLEED LB/MIN	APU FSHP	SHP SOURCE	FUEL BURNED
ELEC CHECKOUT	.250	0.	130.0	29.1	0.0	9.8	56.8	APU	9.0 LB
HYD CHECKOUT	.250	0.	130.0	22.9	0.0	9.8	50.6	APU	8.5 LB
MAIN ENG1 START	.008	0.	130.0	14.0	0.0	8.8	38.9	APU	.3 LB
MAIN ENG2 START	.008	0.	130.0	14.0	0.0	8.8	38.9	APU	.3 LB
STANDBY	.083	0.	130.0	33.0	0.0	9.8	0.0	ME	3.9 LB
CRUISE	3.000	4000.	95.0	31.0	0.0	9.8	0.0	ME	92.3 LB

TOTAL SPS INST. WT. 365.86 LB. SPS INST. WT. PENALTY 951.24 LB. SPS EXPENDABLE WT. PENALTY 239.69 LB.
TOTAL SPS INST. VOL. 4.51 CU. FT.

	REFERENCE SYSTEM VALUES	ALTERNATE SYSTEM DELTA	IMPROVEMENT MULTIPLIER	PERCENT IMPROVEMENT	WEIGHTING FACTOR	WEIGHTED PERCENT IMPROVEMENT
SYSTEM WEIGHT	294.65 LB	-2.50	-1	.85	.10	.085
SYSTEM VOLUME	4.56 CU FT	-.05	-1	1.10	.05	.055
TOG. PENALTY	1197.43 LB	-6.50	-1	.54	.40	.217
RELIABILITY-MTBF	524.00 HRS	1.00	+1	.19	.10	.02
MAINTAINABILITY-MMH/FH	.081	-.001	-1	1.23	.05	.062
AVAILABILITY	99.46	0.00	+1	0.00	.05	0.000
SYSTEM VULNERABILITY	100.00	-4.00	-1	4.00	.02	.080
AIRCRAFT COMPLEXITY	100.00	-2.00	-1	2.00	.05	.100
SPS COMPLEXITY	100.00	-5.00	-1	5.00	.05	.250
LIFE CYCLE COST	100.00	.37	-1	-.37	.13	-.048
SPS TOTAL WEIGHTED PERCENT IMPROVEMENT						.819

APPENDIX II
PRELIMINARY SPS ELIMINATION SUMMARY

TABLE LXVII. TECHNOLOGY LEVEL I

System	SPS Improvement (pct)	System	SPS Improvement (pct)
WITHOUT ECS			
1.3.3.0	-43.035	1.2.1.0	-14.663
1.1.3.0	-42.189	1.1.0.2	-12.162
1.2.3.0	-38.649	2.4.2.0	- 9.667
1.2.0.3	-29.879	1.4.2.0	- 9.590
1.3.2.0	-25.333	1.3.0.1	- 9.405
2.4.3.0	-23.211	1.0.0.2	- 9.165
1.4.3.0	-22.823	1.1.0.1	- 9.037
1.1.1.0	-22.382	1.2.0.1	- 8.364
1.0.0.3	-22.173	2.4.1.0	- 3.944
1.3.1.0	-20.796	1.4.1.0	- 3.711
1.2.2.0	-19.696	1.0.0.1	- 0.319
1.1.2.0	-18.629	2.4.0.1	- 0.233
1.1.0.3	-18.209	1.4.0.1	- 0.000
1.2.0.2	-16.149		
WITH ECS			
1.1.3.0	-20.257	1.2.0.1	-6.651
1.3.1.0	-15.683	2.4.3.0	-5.952
1.3.3.0	-15.412	1.4.3.0	-5.791
1.1.0.3	-15.187	1.0.0.3	-5.699
1.2.1.0	-15.067	1.2.0.2	-3.478
1.1.0.2	-13.374	1.4.2.0	-1.794
1.1.2.0	-11.874	2.4.2.0	-1.536
1.1.1.0	-11.687	1.4.1.0	-1.450
1.3.2.0	-10.882	1.0.0.2	-1.243
1.2.0.3	-10.707	2.4.1.0	-1.192
1.1.0.1	-10.256	1.4.0.1	0.000
1.3.0.1	-10.079	1.0.0.1	0.146
1.2.2.0	- 8.968	2.4.0.1	0.246
1.2.3.0	- 6.975		

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TABLE LXVIII. TECHNOLOGY LEVEL II

System	SPS Improvement (pct)	System	SPS Improvement (pct)
WITHOUT ECS			
1.3.3.0	-45.150	1.2.1.0	-14.561
1.2.3.0	-38.264	1.0.0.2	-12.795
1.1.3.0	-37.050	1.4.2.0	-12.467
1.2.0.3	-32.361	2.4.2.0	-12.454
1.3.2.0	-27.785	1.1.0.2	-11.397
1.0.0.3	-25.855	1.3.0.1	- 9.845
2.4.3.0	-25.575	1.1.0.1	- 8.756
1.4.3.0	-25.035	1.2.0.1	- 7.463
1.3.1.0	-21.712	2.4.1.0	- 5.477
1.2.2.0	-21.139	1.4.1.0	- 5.372
1.1.0.3	-19.615	1.0.0.1	- 0.937
1.2.0.2	-18.373	2.4.0.1	- 0.089
1.1.2.0	-15.865	1.4.0.1	- 0.000
1.1.1.0	-15.471		
WITH ECS			
1.1.3.0	-22.649	1.0.0.3	- 7.922
1.3.3.0	-22.234	1.2.0.2	- 7.762
1.3.1.0	-20.296	1.4.3.0	- 6.691
1.1.0.3	-16.832	2.4.3.0	- 6.205
1.2.3.0	-16.654	1.2.0.1	- 6.125
1.2.1.0	-13.688	1.4.1.0	- 3.398
1.2.0.3	-13.311	2.4.1.0	- 3.075
1.3.2.0	-12.504	1.0.0.2	- 2.401
1.1.0.2	-12.280	1.4.2.0	- 2.294
1.1.2.0	-12.048	2.4.2.0	- 1.476
1.1.1.0	-11.779	1.0.0.1	- 0.442
1.3.0.1	-10.469	1.4.0.1	- 0.000
1.2.2.0	- 9.002	2.4.0.1	0.906
1.1.0.1	- 8.534		

TABLE LXIX. TECHNOLOGY LEVEL IIJ			
System	SPS Improvement (pct)	System	SPS Improvement (pct)
WITHOUT ECS			
1.3.3.0	-41.286	1.0.0.2	-13.633
1.1.3.0	-32.472	2.4.2.0	-12.042
1.2.3.0	-31.826	1.4.2.0	-11.827
1.2.0.3	-30.285	1.3.0.1	- 9.052
1.3.2.0	-26.750	1.2.1.0	- 8.789
1.0.0.3	-24.269	1.1.0.2	- 8.493
2.4.3.0	-22.756	1.1.0.1	- 5.727
1.4.3.0	-22.541	1.2.0.1	- 5.335
1.2.2.0	-18.157	2.4.1.0	- 2.647
1.1.0.3	-17.625	1.4.1.0	- 2.432
1.3.1.0	-17.358	1.0.0.1	- 2.365
1.2.0.2	-16.324	2.4.0.1	- 0.215
1.1.2.0	-14.115	1.4.0.1	0.000
1.1.1.0	-13.947		
WITH ECS			
1.1.3.0	-24.151	2.4.3.0	- 7.862
1.3.3.0	-23.647	1.4.3.0	- 7.817
1.1.0.3	-18.538	1.1.0.1	- 7.761
1.3.1.0	-17.660	1.2.0.2	- 7.759
1.2.3.0	-15.605	1.2.0.1	- 4.880
1.2.0.3	-14.359	1.0.0.2	- 4.664
1.1.1.0	-14.308	1.4.2.0	- 3.334
1.3.2.0	-13.956	2.4.2.0	- 2.977
1.1.0.2	-12.277	1.0.0.1	- 1.916
1.1.2.0	-11.829	1.4.1.0	- 1.726
1.0.0.3	-11.760	2.4.1.0	- 1.369
1.3.0.1	-10.035	1.4.0.1	0.000
1.2.1.0	- 9.532	2.4.0.1	0.357
1.2.2.0	- 8.729		

APPENDIX III

SPS REFERENCE SYSTEM MAINTENANCE ANALYSIS

TABLE LXX. PREVENTIVE AND SERVICING MAINTENANCE, TECHNOLOGY LEVELS I, II, AND III

ASSEMBLY/PART	TASK DESCRIPTION	LEVEL OF MAINTENANCE		CREW SIZE	ELAPSED TIME HR	TOTAL MMH PER TASK	FREQUENCY 1000 FH	MMH 1000 FH	ELAPSED TIME 1000 FH
Secondary Power System	Visual Inspection	Org		1	0.1666	0.1666	333.000	55.478	55.478
APU	Oil Change	Org			0.1333	0.1333	0.667	0.089	0.089
Accessory Gearbox	Oil Change	Org			0.1333	0.1333	1.000	0.133	0.133
Preventive and Servicing Subtotal							334.667	55.700	55.700

*Flight hours

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TABLE LXXI. CORRECTIVE MAINTENANCE, TECHNOLOGY LEVEL I

ASSEMBLY/PART	TASK DESCRIPTION	LEVEL OF MAINTENANCE		CREW SIZE	ELAPSED TIME HR	TOTAL MMH PER TASK	FREQUENCY 1000 FH	MMH 1000 FH	ELAPSED TIME 1000 FH
Hydraulic Pump Package (2)	1. Replace	Org		1	0.500	0.500	1.960	0.980	0.980
	2. Repair	Direct		1	0.750	0.750	0.300	0.225	0.225
	3. Overhaul (specified @ 1200 hr)	Depot		1	6.000	6.000	1.660	9.996	9.996
Electric Generator (2)	1. Replace (6000 hr life specified)	Org		1	0.333	0.333	0.460	0.153	0.153
	2. Repair	Gen/Depot		1	3.000	3.000	0.460	1.380	1.380
Electric Sys Components									
(1) Gen Control Unit (2)	1. Replace	Org		1	0.150	0.150	0.300	0.045	0.045
	2. Repair	Gen/Depot		1	1.333	1.333	0.300	0.400	0.400
(2) Trans. Rectifier (2)	1. Replace	Org		1	0.333	0.333	0.100	0.033	0.033
(3) Contactors (2)	1. Replace	Org		1	0.333	0.333	0.060	0.020	0.020
Bleed Air Heater	1. Replace	Org		1	1.250	1.250	0.020	0.025	0.025
	2. Repair	Direct/Gen		1	3.000	3.000	0.020	0.060	0.060
ATS (2)	1. Replace	Org		1	0.166	0.166	0.200	0.033	0.033
	2. Overhaul	Gen/Depot		1	3.250	3.250	0.200	0.650	0.650
ATS Valves (2)	1. Replace	Org		1	0.166	0.166	0.400	0.066	0.066
	2. Overhaul	Depot		1	4.750	4.750	0.400	1.900	1.900
Elect Fan Motor	1. Replace	Org		1	0.250	0.250	0.050	0.012	0.012
	2. Repair	Gen/Depot		1	3.000	3.000	0.050	0.150	0.150
APU Start System (Hydraulic)	1. Replace	Direct		1	1.000	1.000	0.200	0.280	0.280
	2. Repair	Gen/Depot		1	1.000	1.000	0.093	0.093	0.093
	3. Overhaul (specified @ 1790 start cycles)	Depot		1	8.000	8.000	0.187	1.500	1.500
APU Complete	1. Replace	Org/Direct		2	1.750	3.500	0.465	1.628	0.814
	2. Repair	Org/Direct		1	4.500	4.500	0.300	1.350	1.350
	3. Overhaul	Depot		1	35.000	35.000	0.165	5.775	5.775
APU Shaft to Gearbox	1. Replace	Org		1	0.500	0.500	0.174	0.087	0.087
	2. Overhaul (specified @ 2000 hr)	Gen/Depot		1	1.000	1.000	0.167	0.167	0.167

*Flight hours

TABLE LXXI - Concluded

ASSEMBLY/PART	TASK DESCRIPTION	LEVEL OF MAINTENANCE		CREW SIZE	ELAPSED TIME HR	TOTAL MMH PER TASK	FREQUENCY 1000 FH	MMH 1000 FH	ELAPSED TIME 1000 FH
Accessory Gearbox	**1. Replace**	**Org/Direct**		2	3.500	7.000	0.300	2.100	1.050
	2. Repair	**Depot**		1	9.000	9.000	0.300	2.700	2.700
Corrective M Total							9.371	31.808	29.944
Preventive and Corrective M Total								87.508	
	MTTR = $\frac{29.944}{9.371}$ = 3.195 **hr**								
	MMH/FH = $\frac{87.508}{1000}$ = 0.088 **hr**								
	SPS with ECS								
ECS (Refrig Pkg)	**1. Replace**	**Org/Direct**		1	1.500	1.500	1.037	1.555	1.555
	2. Repair	**Gen/Depot**		1	1.500	1.500	.370	0.555	0.555
	3. Overhaul (Specified @ 1500 hr)	**Depot**		1	10.000	10.000	.667	6.670	6.670
Corrective Total							11.445	40.588	38.724
Preventive and Corrective Total								96.288	
	MTTR = $\frac{38.724}{11.445}$ = 3.383 **hr**								
	MMH/FH = $\frac{96.288}{1000}$ = 0.096 **hr**								

TABLE LXXII. CORRECTIVE MAINTENANCE, TECHNOLOGY LEVEL II

ASSEMBLY/PART	TASK DESCRIPTION	LEVEL OF MAINTENANCE		CREW SIZE	ELAPSED TIME HR	TOTAL MMH PER TASK	FREQUENCY 1000 FH	MMH 1000 FH	ELAPSED TIME 1000 FH
Hydraulic Pump Package (2)	1. Replace	Org		1	0.500	0.500	1.920	0.960	0.960
	2. Repair	Direct		1	0.750	0.750	.260	0.195	0.195
	3. Overhaul	Depot		1	5.500	5.500	1.660	9.130	9.130
Electric Generator (2)	1. Replace	Org		1	0.333	0.333	0.450	0.149	0.149
	2. Repair	Gen/Depot		1	2.750	2.750	0.450	1.238	0.124
Electric System Components									
(1) Gen Control Unit (2)	1. Replace	Org		1	0.150	0.150	0.250	0.038	0.038
	2. Repair	Gen/Depot		1	1.000	1.000	0.250	0.250	0.250
(2) Trans Rectifier (2)	1. Replace	Org		1	0.333	0.333	0.090	0.030	0.030
(3) Contactors (2)	1. Replace	Org		1	0.333	0.333	0.055	0.018	0.018
Bleed Air Heater	1. Replace	Org		1	1.000	1.000	0.016	0.016	0.016
	2. Repair	Direct/Gen		1	2.750	2.750	0.016	0.044	0.044
ATS (2)	1. Replace	Org		1	0.166	0.166	0.160	0.027	0.027
	2. Overhaul	Gen/Depot		1	3.000	3.000	0.160	0.480	0.480
ATS Valves (2)	1. Replace	Org		1	0.166	0.166	0.300	0.050	0.050
	2. Overhaul	Depot		1	4.250	4.250	0.300	1.275	1.275
Elec Fan Motor	1. Replace	Org		1	0.250	0.250	0.040	0.010	0.010
	2. Repair	Gen/Depot		1	2.750	2.750	0.040	0.110	0.110
APU Start System (Hydraulic)	1. Replace	Direct		1	1.000	1.000	0.260	0.260	0.260
	2. Repair	Gen/Depot		1	1.000	1.000	0.086	0.086	0.086
	3. Overhaul	Depot		1	7.500	7.500	0.174	1.305	1.305
APU Complete	1. Replace	Org/Direct		2	1.500	3.000	0.416	1.248	0.624
	2. Repair	Org/Direct		1	4.000	4.000	0.283	1.132	1.132
	3. Overhaul	Depot		1	30.000	30.000	0.133	3.990	3.990
Shaft, APU to Gearbox	1. Replace	Org		1	0.500	0.500	0.105	0.053	0.053
	2. Overhaul	Gen/Depot		1	1.000	1.000	0.105	0.105	0.105

TABLE LXXII - Concluded

ASSEMBLY/PART	TASK DESCRIPTION	LEVEL OF MAINTENANCE	AFSC	CREW SIZE	ELAPSED TIME HR	TOTAL MMH PER TASK	FREQUENCY 1000 FH	MMH 1000 FH	ELAPSED TIME 1000 FH
Accessory Gearbox	1. Replace 2. Repair	Org/Direct Depot		2 1	3.000 8.000	6.000 8.000	0.250 0.250	1.500 2.000	1.500 2.000
Corrective M Total Preventive and Corrective M Total	$MTTR = \frac{23.961}{80.479} = 2.826$ hr $MMH/FH = \frac{80.285}{1000} = 0.080$ hr SPS with ECS						8.479	24.585 80.285	23.961
ECS Refrig Pkg	1. Replace 2. Repair 3. Overhaul	Org/Direct Gen/Depot Depot		1 1 1	1.250 1.250 8.000	1.250 1.250 8.000	0.763 0.287 0.476	0.954 0.359 3.808	0.954 0.359 3.808
Corrective M Total Preventive and Corrective M Total	$MTTR = \frac{29.082}{10.005} = 2.907$ hr $MMH/FH = \frac{85.406}{1000} = 0.085$ hr						10.005	29.706 85.406	29.082

TABLE LXXIII. CORRECTIVE MAINTENANCE, TECHNOLOGY LEVEL III

ASSEMBLY/PART	TASK DESCRIPTION	LEVEL OF MAINTENANCE		CREW SIZE	ELAPSED TIME 1000 FH	TOTAL MMH PER TASK	FREQUENCY 1000 FH	MMH 1000 FH	ELAPSED TIME 1000 FH
Hydraulic Pump Package (2)	1. Replace	Org		1	0.417	0.417	1.900	0.792	0.792
	2. Repair	Direct		1	0.500	0.500	0.240	0.120	0.120
	3. Overhaul	Depot		1	5.000	5.000	1.660	8.300	8.300
Electric Generator (2)	1. Replace	Org		1	0.250	0.250	0.440	0.110	0.110
	2. Repair	Gen/Depot		1	2.250	2.250	0.440	0.990	0.990
Electric System Components									
(1) Gen Control Unit (2)	1. Replace	Org		1	0.150	0.150	0.236	0.035	0.035
(2) Trans Rectifier (2)	1. Replace	Org		1	0.250	0.250	0.080	0.020	0.020
(3) Contractors (2)	1. Replace	Org		1	0.250	0.250	0.050	0.013	0.013
Bleed Air Heater	1. Replace	Org		1	0.750	0.750	0.013	0.010	0.010
	2. Repair	Direct/Gen		1	2.250	2.250	0.013	0.030	0.030
ATS (2)	1. Replace	Org		1	0.166	0.166	0.130	0.022	[illegible].022
	2. Overhaul	Gen/Depot		1	2.000	2.000	0.130	0.260	0.2[illegible]
ATS Valves (2)	1. Replace	Org		1	0.166	0.166	0.250	0.042	0.042
	2. Overhaul	Depot		1	3.750	3.750	0.250	0.938	0.938
Elec Fan Motor	1. Replace	Org		1	0.166	0.166	0.030	0.005	0.005
	2. Repair	Gen/Depot		1	2.000	2.000	0.030	0.060	0.060
APU Start System (Hydraulic)	1. Replace	Direct		1	1.000	1.000	0.230	0.230	0.230
	2. Repair	Gen/Depot		1	1.000	1.000	0.076	0.076	0.076
	3. Overhaul	Depot		1	7.000	7.000	0.154	1.078	1.078
APU Complete	1. Replace	Org/Direct		2	1.250	2.500	0.333	0.833	0.41[illegible]
	2. Repair	Org/Direct		1	3.000	3.000	0.222	0.666	0.66[illegible]
	3. Overhaul	Depot		1	25.000	25.000	0.111	2.775	2.77[illegible]
Shaft, APU to Gearbox	1. Replace	Org		1	0.500	0.500	0.070	0.035	0.03[illegible]
	2. Overhaul	Gen/Depot		1	1.000	1.000	0.070	0.070	0.070

TABLE LXXIII - Concluded

ASSEMBLY/PART	TASK DESCRIPTION	LEVEL OF MAINTENANCE		CREW SIZE	ELAPSED TIME HR	TOTAL MMH PER TASK	FREQUENCY 1000 FH	MMH 1000 FH	ELAPSED TIME HR
Accessory Gearbox	1. Replace	Org/Direct		1	2.250	2.250	0.200	0.450	0.450
	2. Repair	Depot		1	6.500	6.500	0.200	1.300	1.300
Corrective M Total							6.558	19.260	18.843
Preventive and Corrective M Total								74.960	
	$MTTR = \frac{18.843}{6.558} = 2.873$ hr								
	$MMH/FH = \frac{74.960}{1000} = 0.075$ hr								
	SPS with ECS								
ECS (Refrig Pkg)	1. Replace	Org/Direct		1	1.000	1.000	0.555	0.555	0.555
	2. Repair	Gen/Depot		1	1.000	1.000	0.222	0.222	0.222
	3. Overhaul	Depot		1	6.000	6.000	0.333	1.998	1.998
Corrective M Total							7.668	22.035	21.618
Preventive and Corrective M Total								77.735	
	$MTTR = \frac{21.618}{7.668} = 2.820$ hr								
	$MMH/FH = \frac{77.735}{1000} = 0.078$ hr								